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# GEOPHYSICS

VOLUME XIX, NO. 4 OCTOBER, 1954

## TECHNICAL PAPERS

The Present State of Geothermal Investigations — *Francis Birch* — 645
Cross-Correlation Filtering — *Hal J. Jones and John A. Morrison* — 660
Reflection Quality, a Fourth Dimension — *Ben F. Rummerfield* — 684
Surface and Near-Surface Waves in the Delaware Basin — *Milton B. Dobrin, Philip L. Lawrence, and Raymond Sengbush* — 695
Effects of Weathering on Refraction Depths Calculated on a Time-Intercept Method and Break-Point Method — *N. N. Zirbel* — 716
The Method of Cagniard in Seismic Pulse Problems — *C. Hewitt Dix* — 722
Mapping Nearly Vertical Discontinuities by Earth Resistivities — *Ö. Logn* — 739
Interpretation of Resistivity Data over Filled Sinks — *Kenneth L. Cook and Robert G. Van Nostrand* — 761
Geophysical History of the Good Field, Borden County, Texas — *Holland C. McCarver* — 791
Performance of Resonant Seismometers — *William L. Donn, Maurice Ewing, and Frank Press* — 802

## NON-TECHNICAL PAPER

Geophysical Management Looks at Safety as a Public Relations Factor — *Cecil H. Green* — 820

## DEPARTMENTS

Patents 825
Reviews 831
Memorials
David M. Weber; Hubert Lückerath 840
Contributors 844
Society Round Table
Committees 849
Announcements 856
Personal Items 859
Constitution and Bylaws 862
Index to Volume XIX 872

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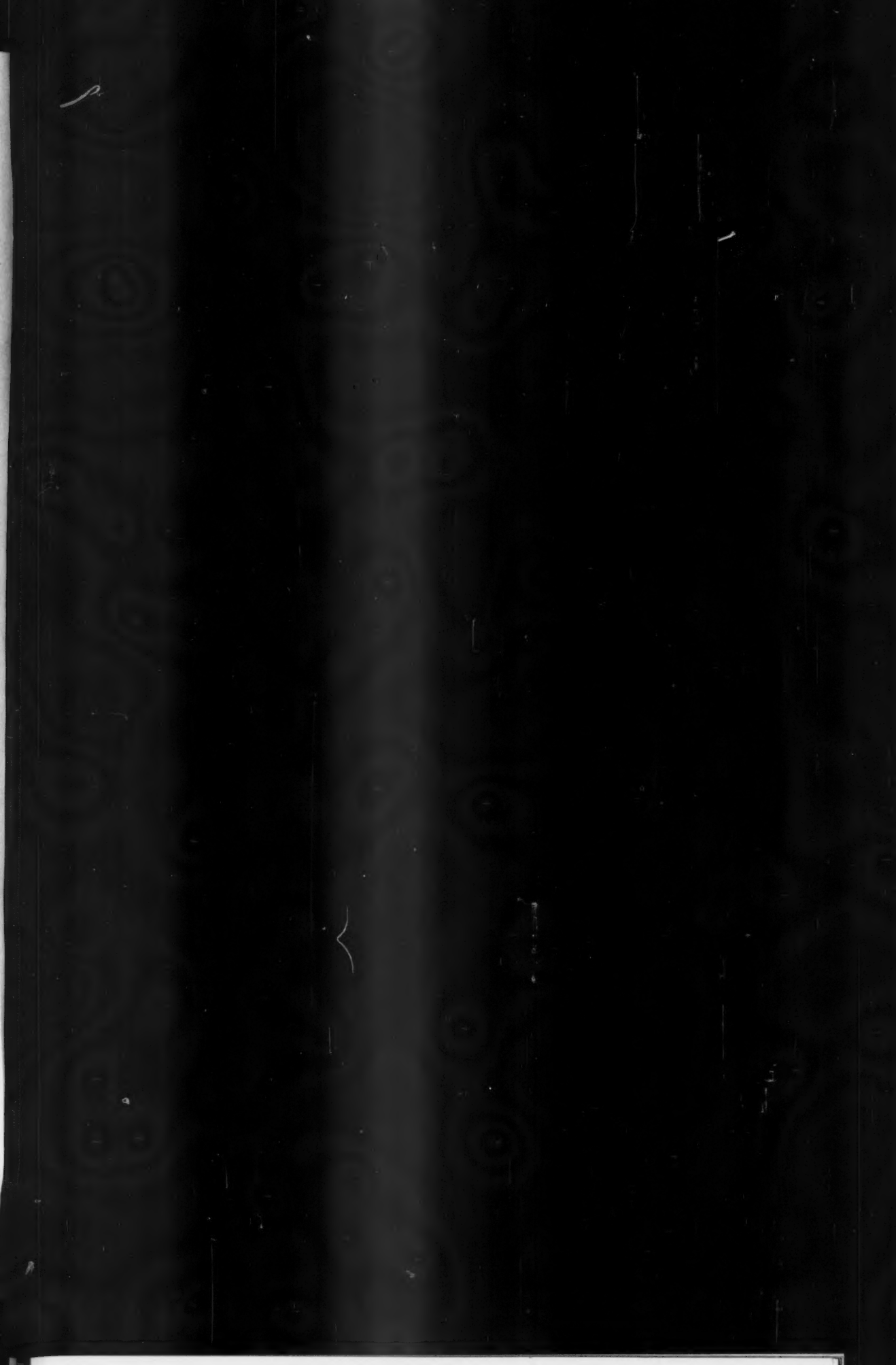

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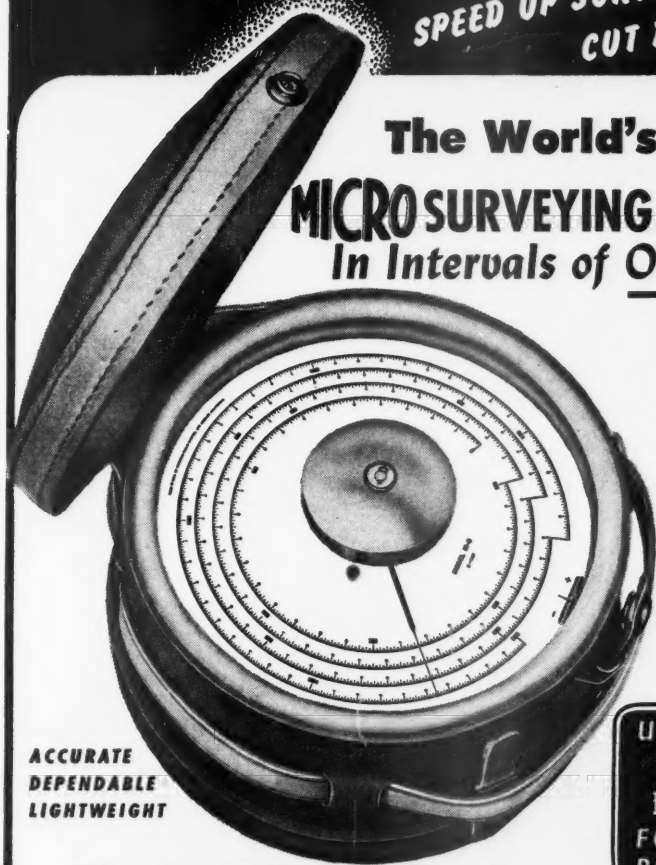

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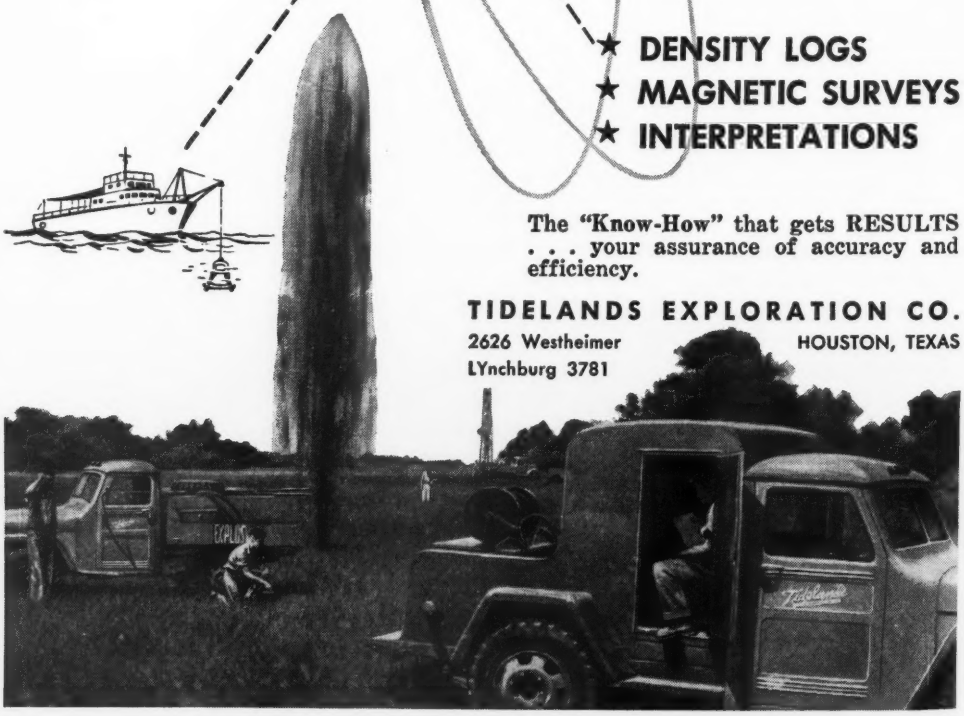

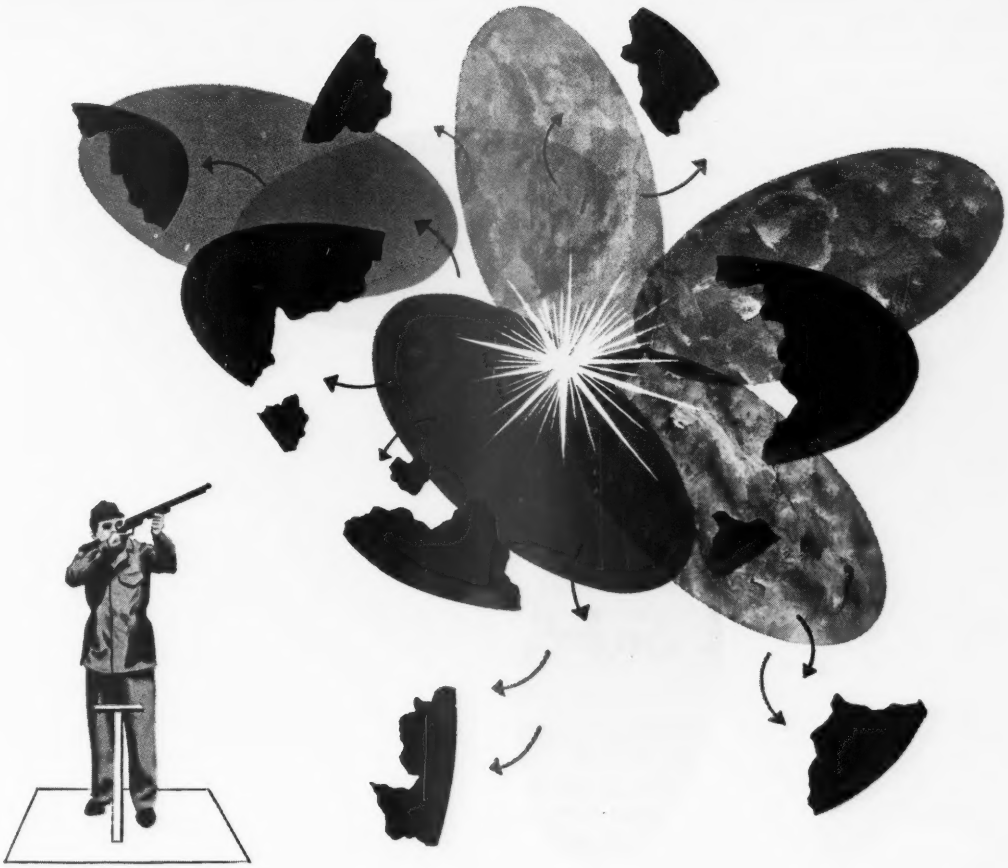

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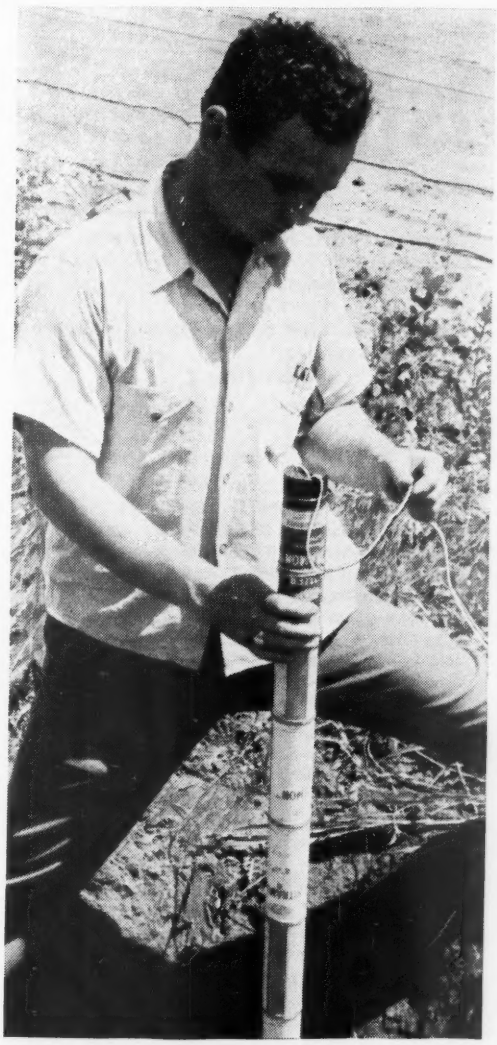

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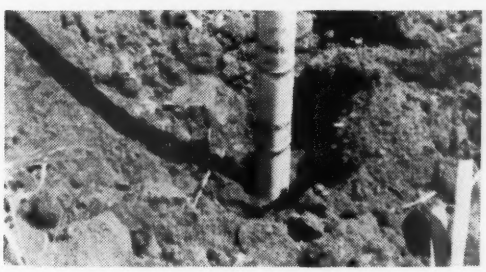

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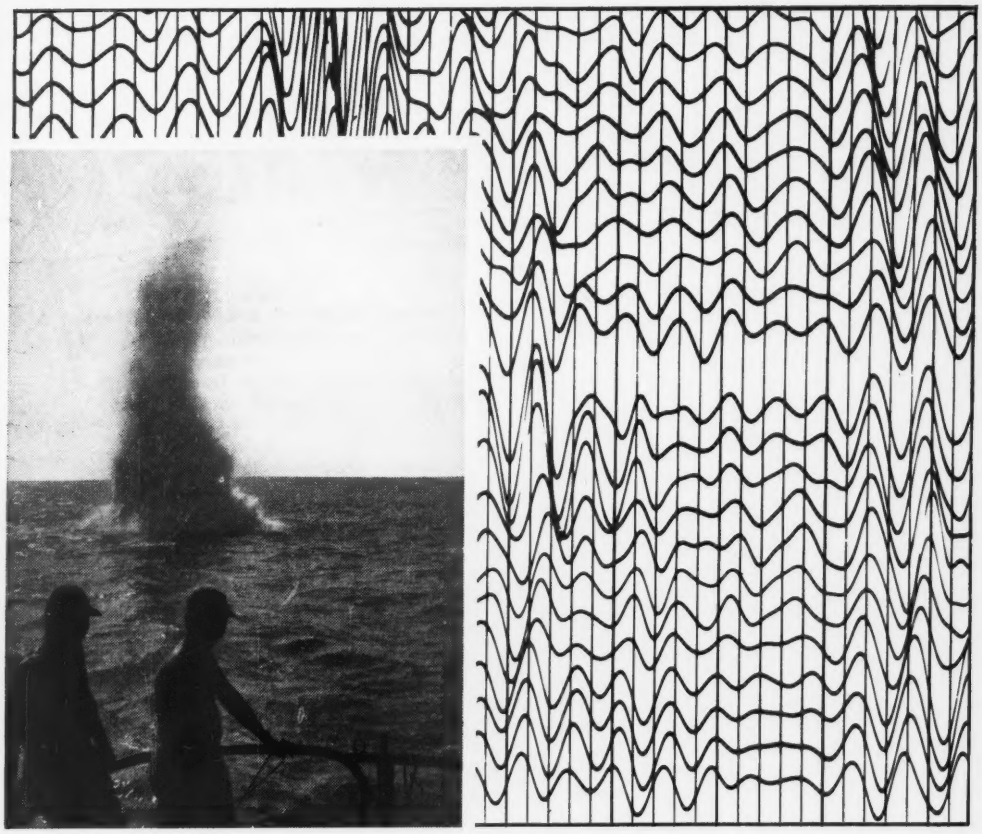

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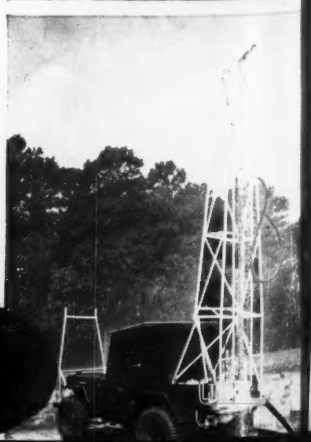

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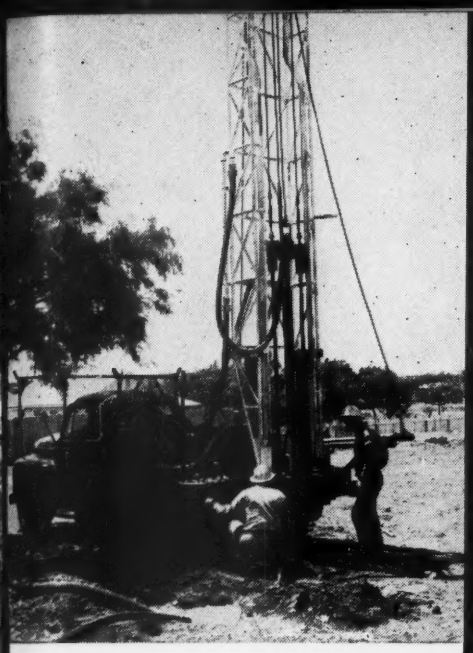

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Geophysical Societies begin on page ... 24

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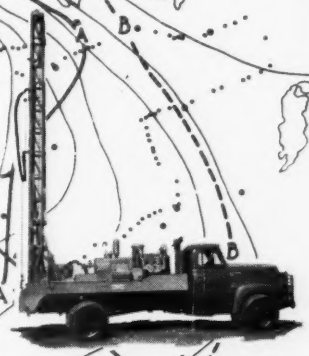

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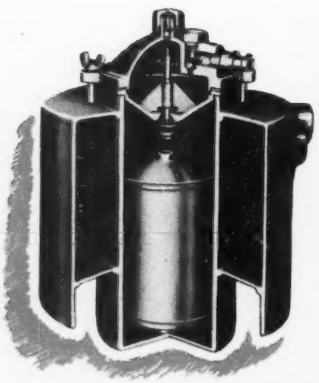

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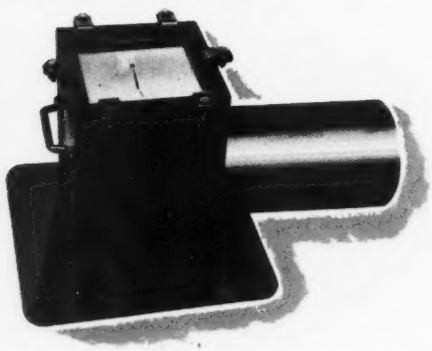

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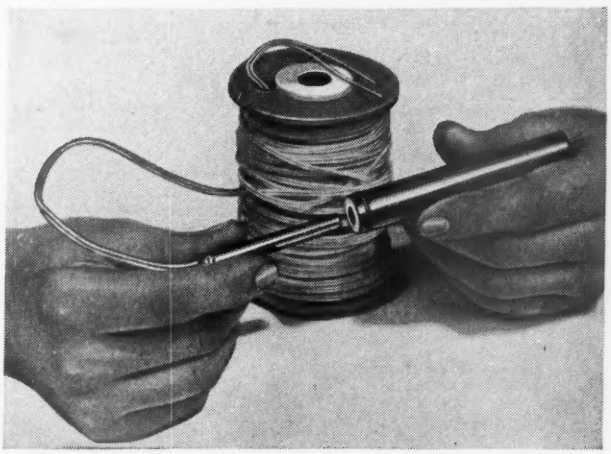

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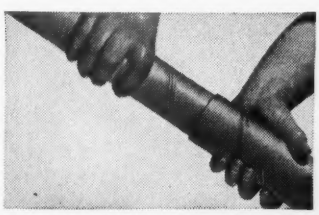

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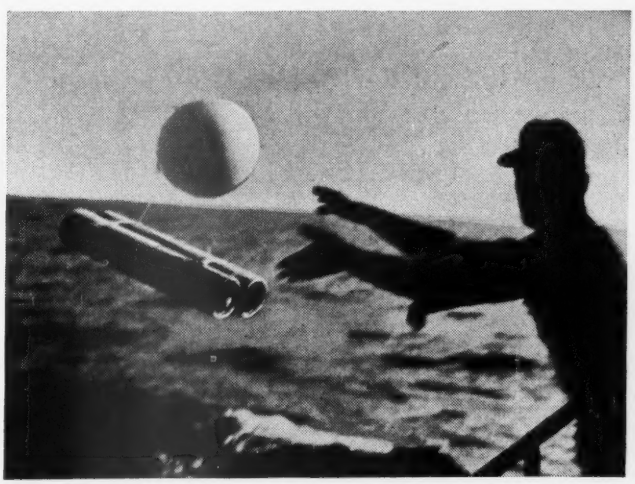

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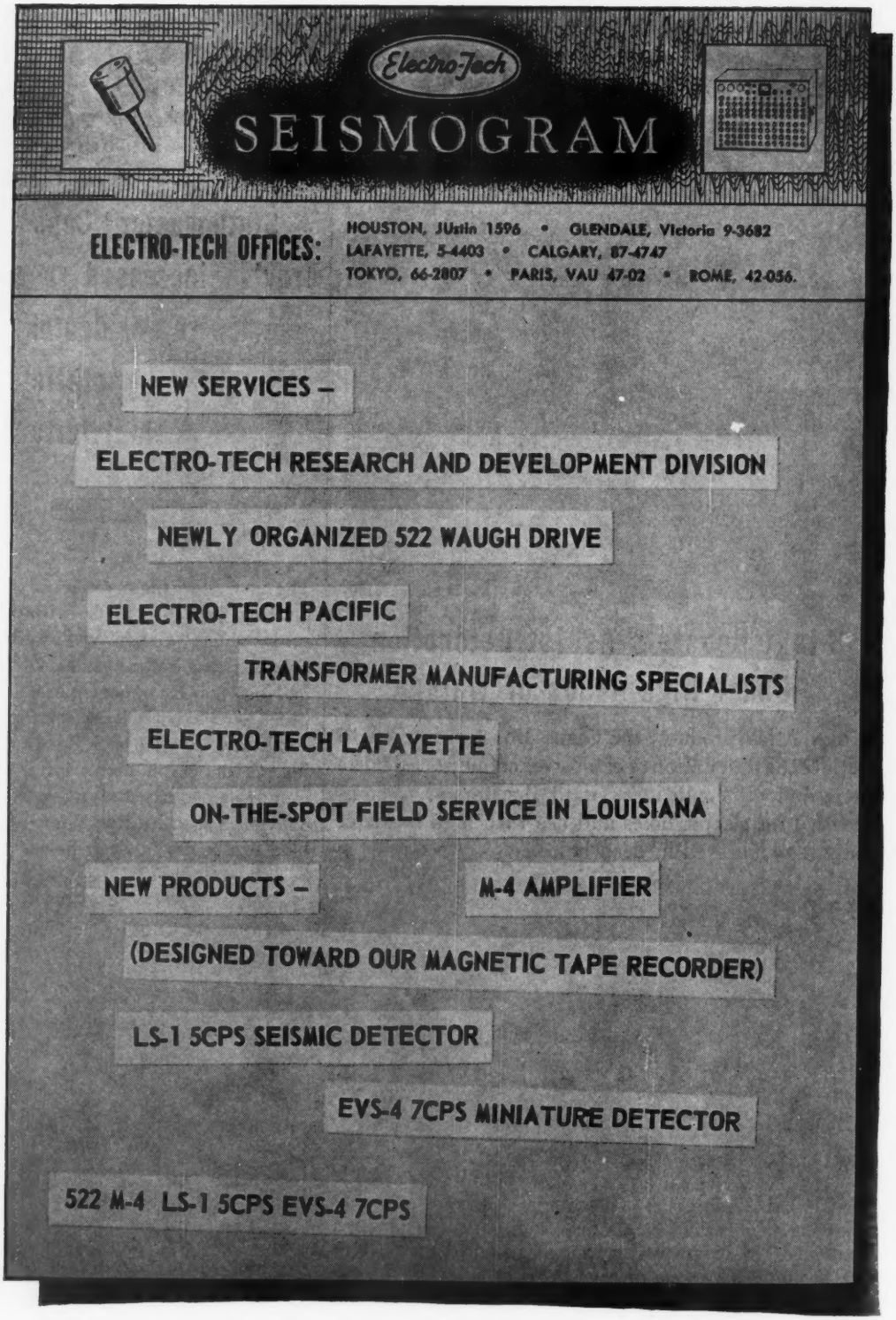
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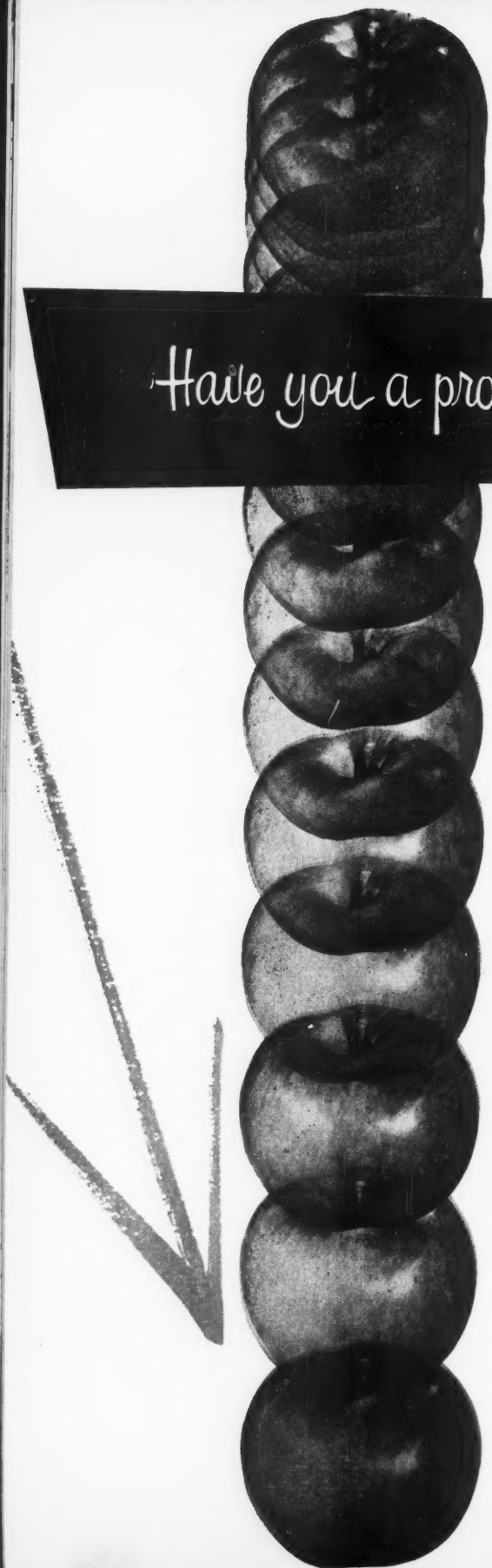

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# GEOPHYSICS

## TECHNICAL PAPERS

### THE PRESENT STATE OF GEOTHERMAL INVESTIGATIONS*

FRANCIS BIRCH†

ABSTRACT

At present, the emphasis in geothermal studies in non-volcanic areas is on the flow of heat to the surface, a quantity of much theoretical importance. The number of reliable determinations of heat flow is still small, with few of the oil-producing regions represented. While thermal gradients range from about 5 to 70°C/km, most of the measurements of heat flow fall within the range $1.2 \cdot 10^{-6}$ cal/cm²-sec ± 50%, including the recent values for the deep ocean basins. There are suggestions of regional variations, but many more measurements reliable to 10% or better will be needed for further progress. The study of regions or provinces, rather than single localities, is especially desirable, and should be feasible in areas extensively drilled for oil. The principal requirements, which are difficult to meet, are: 1) approximate thermal equilibrium, which may require an undisturbed period of many months, and 2) availability for laboratory study of cores representing the major formations penetrated by the well. A renewal of interest in this subject among oil geologists, with recognition and exploitation of opportunities as they arise, could greatly advance its development.

#### INTRODUCTION

Although geothermal measurements have many practical applications in the technology of mining, of tunnel construction, and of petroleum production, I shall disregard these applications in the following survey and concentrate instead upon the place of such measurements in geological and geophysical theory, the present state of affairs in geothermal investigations, and some aspects of possible future work of this kind. As a further restriction of the topic, only non-volcanic areas will be considered.

*Magnitude and Probable Sources of Heat Flow in the Earth*

As every miner and well-driller knows, the temperature generally increases with the depth below the surface of the earth or, at least, below a thin layer affected by seasonal variations of surface temperature and by ground water. This rise of temperature with depth shows that the earth is losing heat, but Rayleigh showed, as long ago as 1906, that all of the heat flowing to the surface could be

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† Professor of Geology, Harvard University, Cambridge, Mass.

currently supplied by radioactive heat generation in a layer only a few tens of kilometers thick, if it had the average radioactivity of common rocks. It is now widely believed that both the outward heat flow and the internal temperatures depend mainly upon the distribution of the radioactive elements.

The outward flow of heat by conduction, per unit of surface and per unit of time, is given by the product of the vertical thermal gradient, or rate of increase of temperature with depth, and the thermal conductivity, a coefficient characteristic of the conducting material. Rough values for the conducted heat have long been available: if a gradient of 30°C/km occurs in rock having a thermal conductivity of 0.004 cal/cm-sec-deg, the conducted thermal flow is $1.2 \cdot 10^{-6}$ cal/cm$^2$-sec, or 38 cal/cm$^2$-year, or a total of about $2 \cdot 10^{20}$ cal/year (see, for example, Joly, 1909, p. 76). This is enough, if all used for the purpose, to melt a layer of ice about $\frac{1}{2}$ centimeter thick every year. This may appear to be a trivial amount; it is only one part in about 10,000 of the average solar radiation received by the earth and re-radiated to space, and it contributes a negligible increment to the earth's surface temperature. But over the whole surface, and over the billions of years of geological time, the integrated heat flow represents an immense leakage of energy, probably of much significance for geological dynamics.

To this figure must be added the transport of heat to the surface by hot mobile constituents, such as volcanic ash and lavas, steam, and hot water; most of the estimates of this quantity, admittedly very crude, agree that, whatever local importance such processes undoubtedly have, the total, when averaged over time and space, is but a small fraction of the conducted heat.

*Geological Implications of Heat Flow Data*

Unlike radioactive atoms, radioactive heat is not tagged; it cannot be distinguished from any other kind of heat, so that the measurements of heat flow enable us only to put relatively vague limits on the total amount and distribution of radioactivity. The principal difficulty arises from ignorance of the distribution of radioactivity with depth; the materials of the earth are such poor conductors of heat that heat sources deep in the earth, if there are any, contribute little to the flow of heat at the surface, even after billions of years. There are reasons, however, for doubting whether there remains an appreciable amount of radioactive material deeper than a few hundred kilometers below the surface, and Jeffreys (1952, Chapter X) has, as a limiting case, assumed that all of the radioactivity is concentrated within the outermost 30 km or so. If this were so, then the heat flow to the surface might be very nearly equal to the current rate of heat production by radioactivity. This extreme assumption seems to be consistent with existing measurements of the radioactivity of such common rocks as granites and basalts, and with current views regarding the composition of the continental crust.

A corollary of this theory is that the flow of heat ought to be higher than normal wherever the crust of silica-rich rocks is thicker than normal, as under mountain ranges, and lower than normal in the ocean basins, where this crust is

thin or absent. The first of these expectations seems to be born out by the evidence (Birch, 1950) but the new measurements of heat flow through the ocean bottom lead to the unexpected result that continental and oceanic values of heat flow are about the same. (Revelle and Maxwell, 1952; Bullard, 1952, 1954). This discovery, which we owe to the initiative of Bullard in developing equipment for measuring temperatures in the mud of the deep sea floor, greatly affects our ideas about the distribution of radioactivity. Jeffreys' theory must be modified with respect to the difference between oceans and continents, and probably also with respect to the completeness of concentration of radioactivity within the continental crust. The equality of heat flow between oceans and continents suggests that roughly the same amount of radioactivity underlies each square kilometer (or 100 $km^2$) of surface, whether on land or sea. On the other hand, the high concentration of radioactivity in typically continental rocks is well-established, so that it seems likely that the subcrustal rocks of the oceans are more radioactive than those below the continents.

The determinations of heat flow are significant also for the question of the existence of convection currents in the Earth's mantle, which have been postulated by many geologists as a basis for dynamical geology. Such currents must rise in some areas and descend in others, on a horizontal scale presumably comparable with continental dimensions. We might expect to find large areas characterized by high values of heat flow, over the rising columns, and others with low values of heat flow, over descending columns. The present evidence, so far as it goes, shows no systematic differences between oceans and continents or any other large areas; it is thus adverse, in my opinion, to the existence of major currents on the scale required, at least in the shallower parts of the mantle.

## METHODS FOR MEASURING HEAT FLOW IN THE EARTH

I have said enough, perhaps, to suggest the part which the heat flow plays, or could play if it were better known, in geological theory; let us next see just what information we have about this quantity. First, how is it found? We want the product of thermal gradient by thermal conductivity, at a particular place. This means, in practice, the measurement of temperatures through some finite interval of depth, below the level affected by the annual variation, together with determinations of thermal conductivity of an appropriate number of samples taken from the same interval. Surprising as it may seem, until 1939 this correlation had never been accomplished. In this, as in so many other phases of thermal studies, the initiative was taken by British geophysicists, particularly the Cambridge University group, and we are still indebted to Bullard and his students and collaborators for the greater part of the evidence on this subject. The remarkable outcome of this work was the establishment of the fact that there is relatively small variation of the *heat flow*, as contrasted with more than ten-fold variations of thermal gradient, from about 5 to 70°C/km, if we exclude volcanic areas. These variations of gradient are correlated with variations of thermal resistance having about the same range.

The requirement for suitable samples has proved to be a difficult one. Well cuttings are usually too small to give satisfaction, and cored sections of oil wells too often limited to producing horizons. Samples which are easily altered on removal are undesirable; formations consisting of many thin layers of different properties are evidently difficult to sample. We can thus understand why many of the determinations of heat flow, on land, have been made in "hard rock" areas, in mines or tunnels, where there is usually a plentiful supply of samples of a relatively permanent kind, and often only a small number of massive lithologic units.

The measurements at sea take advantage of the constancy of temperature in the deep oceans; since there is no annual variation of temperature, there is no annual disturbance at shallow depths in the bottom mud. The measurements are made with a probe, a few meters long, driven by free fall into the mud, carrying two temperature-sensitive elements, thermistors or thermocouples. The temperature difference between these two elements is recorded, as a function of time, in a water-tight recording chamber fixed to the probe. Drifting of the vessel makes it undesirable to leave the probe in the bottom for more than 20 to 30 minutes, after which it is withdrawn by its cable. Equilibrium is not reached during the time of burial, but a fairly reliable extrapolation can be made. Coring tubes are lowered in the same region for the collection of samples of the bottom mud, which are preserved for study of the conductivity.

## GEOGRAPHICAL DISTRIBUTION OF DATA ON HEAT FLOW

The world distribution of the measurements of heat flow is shown in Figure 1. A few years ago, there would have been no points for the oceans, but they now dominate the map. A single dot on land often represents a number of individual determinations, probably more reliable than the ones at sea. Nevertheless, the continental distribution is evidently unsatisfactory. In the United States, there are only three reasonably adequate determinations, and only one of these is in an oil-producing area. A summary of the values is shown in Table I. This constitutes the evidence for the statement that there is no significant difference, at present, between oceans and continents. I think that it will be agreed that the amount and distribution of evidence leaves much to be desired. We can depend upon the oceanographers for a rapid increase of oceanic data; but for a significant increase in the continental data it will be necessary to obtain the interest and cooperation of the petroleum geologists and geophysicists.

## SHORTCOMINGS OF AVAILABLE DATA

In the United States, thousands of wells are drilled each year, and one naturally wonders why there are no determinations of heat flow for Texas, or Oklahoma, or Louisiana, or Kansas. There are, in fact, more measurements of temperature for American wells than for the rest of the world, and there may be an impression that study of temperature in oil fields is a closed chapter. In the

TABLE I

REGIONAL AVERAGES OF HEAT FLOW, IN $10^{-6}$ CAL/CM$^2$-SEC

| Region | No. of Determinations | Heat flow | | Authority |
|---|---|---|---|---|
| | | Mean | Range | |
| South Africa | 7 | 1.10 | 0.75–1.52 | Bullard, Krige, 1939 |
| Canada[1] | 8 | 0.96 | 0.69–1.32 | Misener et al., 1951 |
| Iran | 18 | 0.87 | 0.53–1.22 | Coster, 1947 |
| Great Britain[2] | 7 | 1.35 | 0.68–2.87 | Benfield, 1939; Bullard and Niblett, 1951 |
| United States | 3 | | | |
| California | | 1.29 | | Benfield, 1947 |
| Colorado[3] | | 1.7 | | Birch, 1950 |
| Michigan[1] | | 0.93 | | Birch, 1954 |
| Atlantic | 5 | 0.98 | 0.58–1.42 | Bullard, 1954 |
| Pacific | 15 | 1.45 | 0.4–3.3 | Revelle and Maxwell, 1952, and unpublished |

[1] Temperatures taken in mines.
[2] Counting the 4 Eakring wells as one.
[3] Temperatures taken in Adams Tunnel, at mean elevation of 8,300 feet.

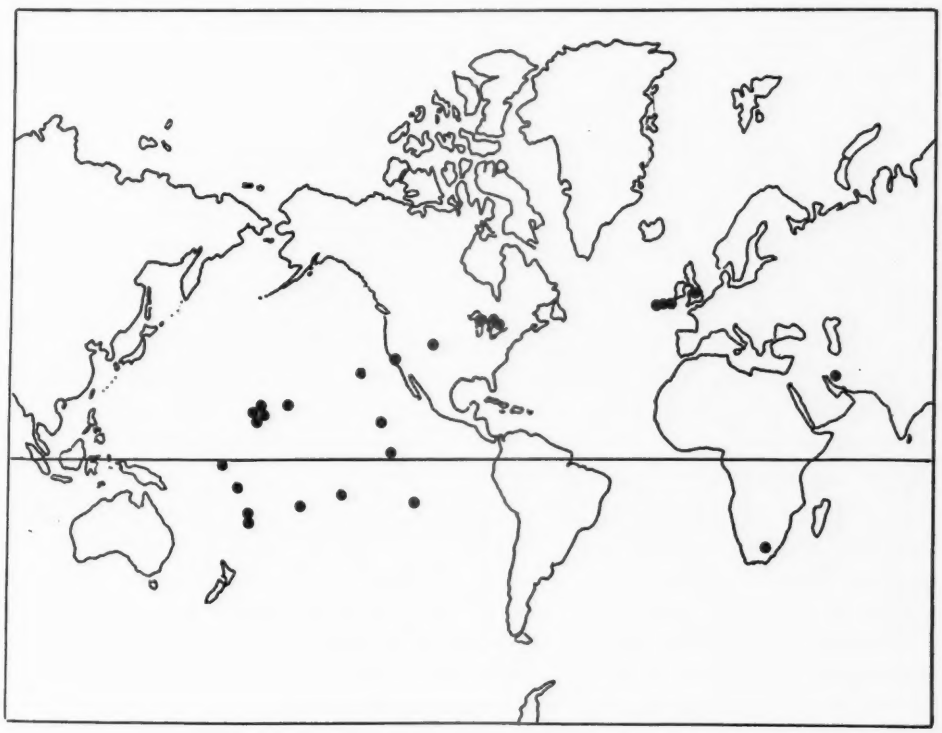

FIG. 1. Geographical distribution of determinations of heat flow to 1954.

1920's, a cooperative program of the American Petroleum Institute and the U. S. Geological Survey led to measurements of temperature, by Dr. C. E. Van Orstrand and others, in hundreds of American wells. These measurements have unique qualities. Much of the drilling in those days was with cable tools, which disturb the rock temperatures much less than rotary drilling with its rapid circulation of mud. Many of the wells had been abandoned or shut in for considerable periods before the temperatures were measured; in some, it was possible to repeat the survey after a year or so. On the whole, this body of temperature measurements, carefully taken one by one with mercury maximum thermometers, is the most extensive and reliable ever obtained.

The principal weakness of this program was in interpretation and, specifically,

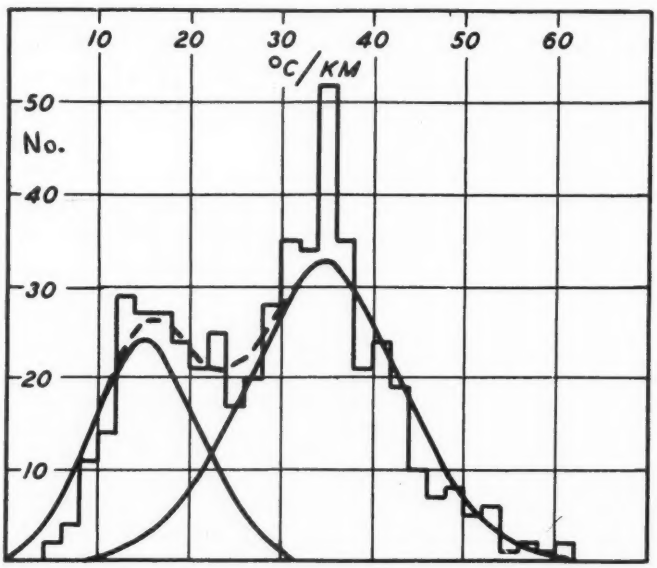


FIG. 2. Frequency distribution of 511 determinations of geothermal gradient, after Landsberg.

in the failure to examine the principal variable which affects thermal gradients, that is, thermal conductivity. It was not appreciated that much could be explained by simple stratigraphic or lithologic correlations. The results were typically presented as least-square straight lines through all of the points found for a given well, or for arbitrary depths, and the slopes of these lines have been discussed statistically by several writers (Van Orstrand, 1935; Landsberg, 1946; Chebotarev, 1952). In Landsberg's paper we find the curve of Figure 2, a frequency curve of mean gradients. The bimodal character of this distribution was noted, and it was suggested that one peak might represent a mean for igneous rocks, the other, for sedimentary rocks. This is hardly tenable, since no more than half-a-dozen measurements were made in igneous rocks; a more plausible correla-

tion would be sandstone and shale, but without going back to the original data it is impossible to say that any particular gradient corresponds to a particular kind of rock, because of the practice of averaging over fixed intervals of depth, rather than over formations or lithologic units.

Consider, for example, the simplest and most idealized situation (Figure 3), an alternation of horizontal layers of uniform, but different, materials. Suppose that the flow of heat is uniform throughout the column. Then the gradients will be proportional to the thermal resistivities of the formations; I have plotted the curve on the assumption that the thermal resistivity of the shale is twice that of the sandstone, a fairly typical ratio. The solid curve gives the temperature distribution; the circles represent the temperatures which would be found on measur-

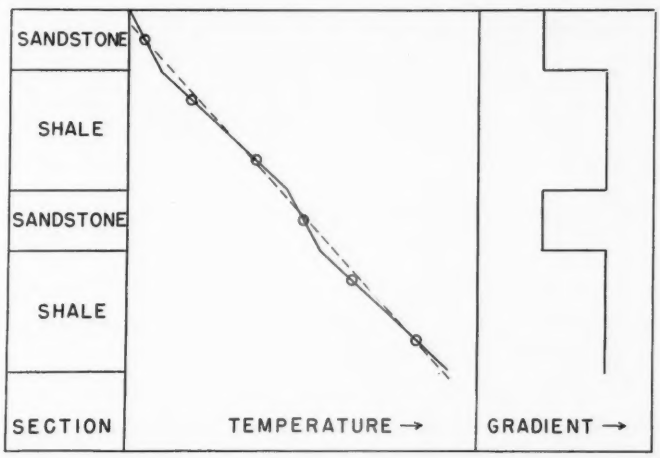


FIG. 3. Temperature and gradient in an idealized sequence of uniform horizontal layers.

ing at fixed intervals of depth. According to the former practice, these points would be plotted as shown, and a straight line (the broken line) passed through the whole set of observations. The gradient of this mean line does not correspond to that for either of the formations, but to some weighted average of the two. The value of a statistical discussion of such averages without examination of the real stratigraphic columns seems very doubtful. A real case, nearly as clear-cut as the ideal one, is shown in Figure 4, reproduced from Van Orstrand (1937). The relatively high conductivity of the salt is clearly indicated, and the change of gradient takes place abruptly.

The situation is usually much more complicated. The individual lithologic units are not necessarily horizontal, or uniform in either thickness or thermal resistivity. There may be alternations on a fine scale between good and poor conductors. There are obvious limitations upon our powers to account for all of the details of the temperature distribution. But the local conductivity is in general the first variable which needs to be examined for the interpretation of the tem-

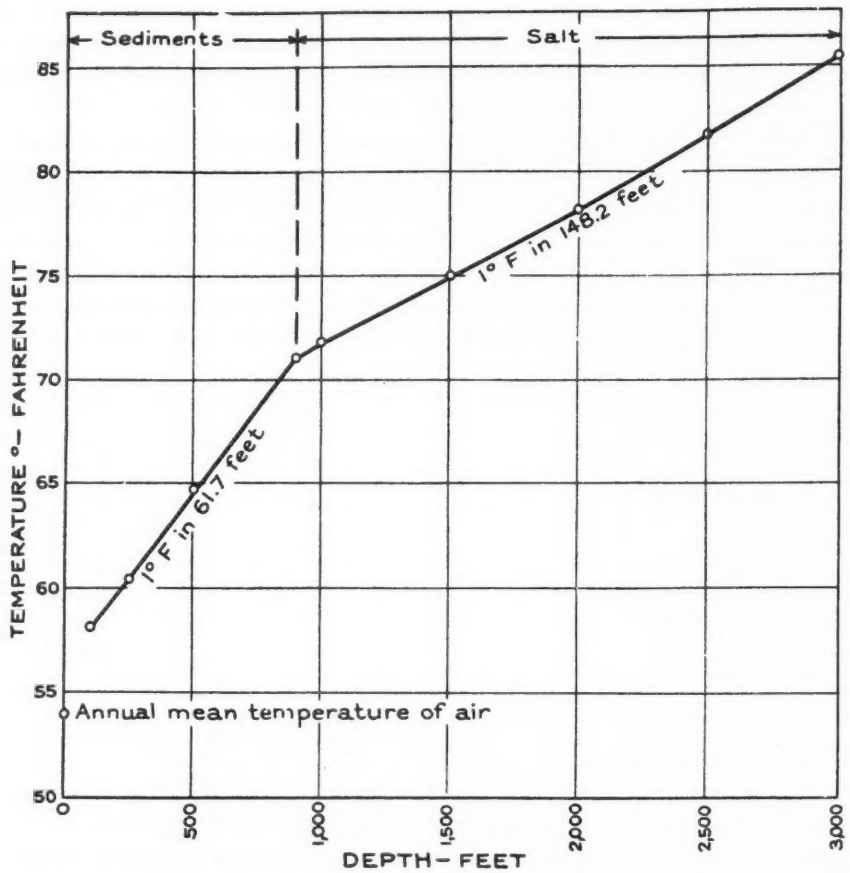


FIG. 4. Observed temperatures, Utah Southern Oil Company, Balsley No. 1, after Van Orstrand.

peratures, and this means, first, a knowledge of the stratigraphy, and second, enough samples to provide representative average values of conductivity or resistivity for the major units.

The factors which determine the thermal conductivity of sedimentary rocks are numerous, and only partly understood; composition, porosity, temperature, grain size and shape, fluid content all have to be considered. Enough sedimentary rocks have been studied, however, to justify a few preliminary generalizations, and we can make some use of principles developed in relation to the conductivity of igneous rocks. We know that the best thermal conductor among the common minerals is quartz; some of the ultrabasic and metamorphic minerals are nearly as good; dolomite is better than calcite. (Birch and Clark, 1940; Clark, 1941). Feldspars, clays, bituminous materials, have the lowest conductivities. In general, we expect the highest conductivities, and the lowest gradients, in quartzites and quartz-rich sandstones of low porosity; the lowest conductivities and highest

gradients in quartz-poor or bituminous shales. We are not yet able to predict the conductivity of rocks of high porosity with much confidence. There is the additional complication that the usual descriptions of sedimentary rocks, as given in well logs, rarely include the information necessary for an estimate of conductivity; they may in fact be highly misleading. There seems to be no satisfactory alternative, at present, to an abundance of samples from the principal layers through which a temperature profile passes. A method of conductivity logging is, perhaps, a possible future development.

There are situations where factors other than conductivity are important in determining the temperature. In mountainous country the topographic effect may be large, and the principal problem may be the calculation of the appropriate correction. The correction is similar to the terrain correction in measurements of gravity. (Jeffreys, 1938; Bullard, 1938; Birch, 1950). Another kind of disturbance which may sometimes be important is produced by movement of water; if there is an appreciable vertical component to the motion, then the amount of conducted heat may be greatly affected locally. A situation perhaps to be explained in this way is described below.

## SOME CORRELATIONS BETWEEN GEOTHERMAL WELL DATA AND REGIONAL GEOLOGY

It seems likely that there are *real* variations of heat flow related to structural and chemical variations on a regional scale, but we are unable to perceive the pattern with the limited number of measurements now available. There has long been an impression that thermal anomalies are associated with oil fields, but without detailed mapping of heat flow in and around such areas this remains a mere hypothesis. Maps showing temperatures or temperature gradients probably reflect mainly the near-surface lithology or structure. As an example let us consider Van Orstrand's data (Van Orstrand, 1937) for wells in the Appalachian Plateau (Fig. 5). These wells are distributed roughly parallel to the strike of the Appalachian structure, but well to the west of the folded belt. They were drilled to the Oriskany sandstone, penetrating flat-lying upper and middle Devonian rocks, with some Carboniferous formations at the surface to the south. Van Orstrand believed that the gradients in these wells were related to the depth to basement, for which the contours are shown on this map. It seems more probable that the variations are closely related to changes of lithology. In Figure 6 I have plotted the mean-gradients for 500-foot, and where possible, for 250-foot intervals, for one of the West Virginia wells; the section is given by I. C. White (1919). The gradients are low in the upper formations, high in the lower ones. This is what is to be expected in terms of the descriptions of these rocks, and the known dependence of conductivity upon rock composition. The upper formations are mainly sands and sandy shales whose conductivity we expect to be relatively high; the lower parts are bituminous marine shales expected to be of low conductivity. The ratio of gradients, roughly two to one, is reasonably in accord with

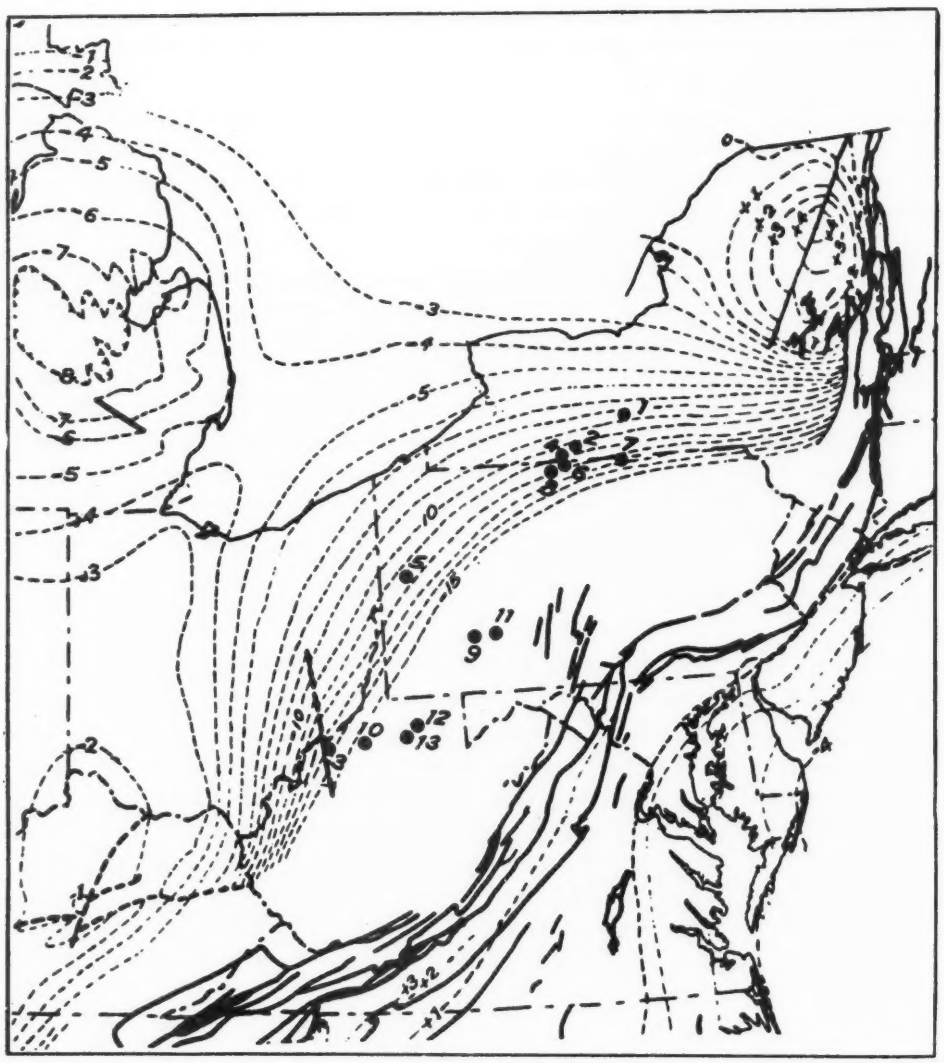

FIG. 5. Location of wells and depth to basement in the Appalachian Plateau, after Van Orstrand.

laboratory measurements of presumably similar materials.

Since the Devonian section changes relatively little along the strike, we might anticipate that the other wells at the same distance from the folded region would show somewhat similar results. All of the wells have been treated in the same way, and Figure 7 shows mean gradients for 500-ft intervals; the profiles have all been aligned on the Oriskany sandstone as a common marker. In spite of the irregularities, there is a marked tendency for the same pattern to persist: low gradients in the upper parts, high gradients in the lower. It would be interesting to show

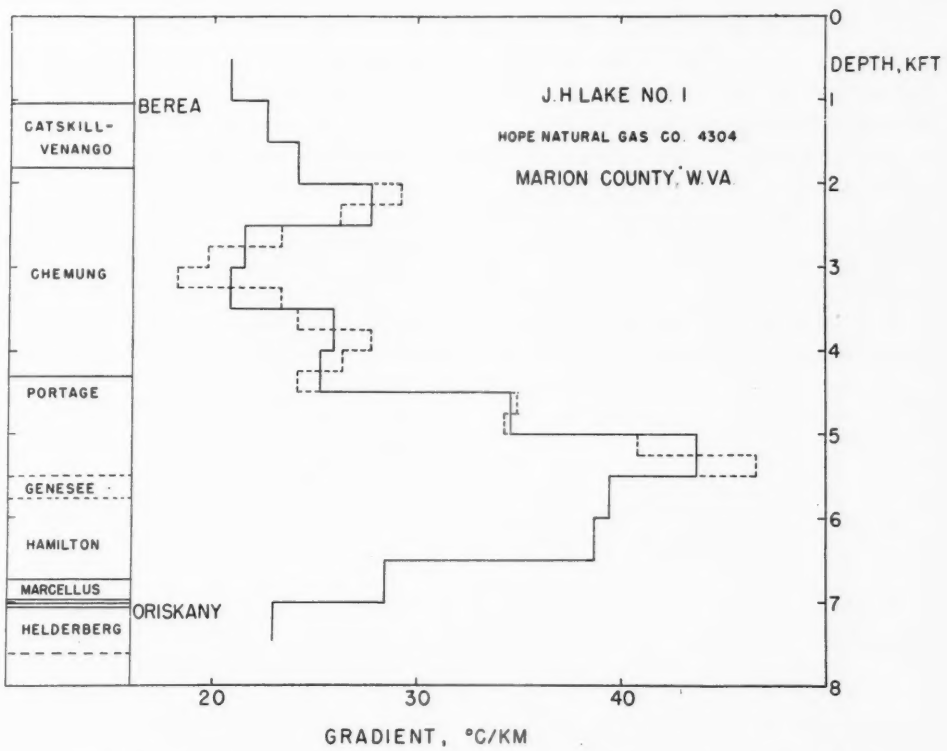


FIG. 6. Gradients for 500-foot (solid) and 250-foot (dashed) intervals, and stratigraphic column, for J. H. Lake No. 1 well, West Virginia (No. 12 of Figure 5).

some other horizons than the Oriskany, but apparently they are difficult to trace by conventional methods. The temperature gradients are perhaps the best indicators of the stratigraphic horizons in these sections.

In order to convert these measurements to determinations of heat flow, it will be necessary to obtain samples of some of the formations. There has been little coring in this region, and samples collected from outcrops in the folded belt are of doubtful value since facies changes are most pronounced in the transverse direction. It may prove possible to collect representative samples from outcrops along the same strike, though cores from neighboring wells would naturally be preferble. As a preliminary estimate, based on a very small number of samples and upon some estimates of conductivity, it is probably safe to say that the heat flow throughout this region is between 1.2 and 1.6 microcal/cm$^2$-sec. The uncertainty could be appreciably reduced with the aid of 20 or 30 well-placed samples.

As another example, I have considered some of the measurements by McCutchin (1930) in wells in central Oklahoma. The striking sections in McCutchin's paper show the isothermal surfaces along two profiles east of Oklahoma City; they have been frequently reproduced, but no plausible explanation

has ever been given of the convergence of the isothermal surfaces to the east; the gradient is two to three times as steep at the eastern edge of this section as at Oklahoma City. In order to clarify the relations to stratigraphy, I have replotted some of McCutchin's measurements on a section taken from Hiestand (1935, p. 963) in Figure 8; this section runs nearly due east from the Oklahoma City field. One fact emerges from this figure: the measurements in the Oklahoma City field are in younger rocks than are those to the east; the stratigraphic units in which the low gradients were found at Oklahoma City are missing east of the Cromwell field. I cannot find evidence, however, that there is any great difference between the rocks above and below the particular horizon with which we are concerned; an additional point is from a report by Carver (1948, p. 337) of a

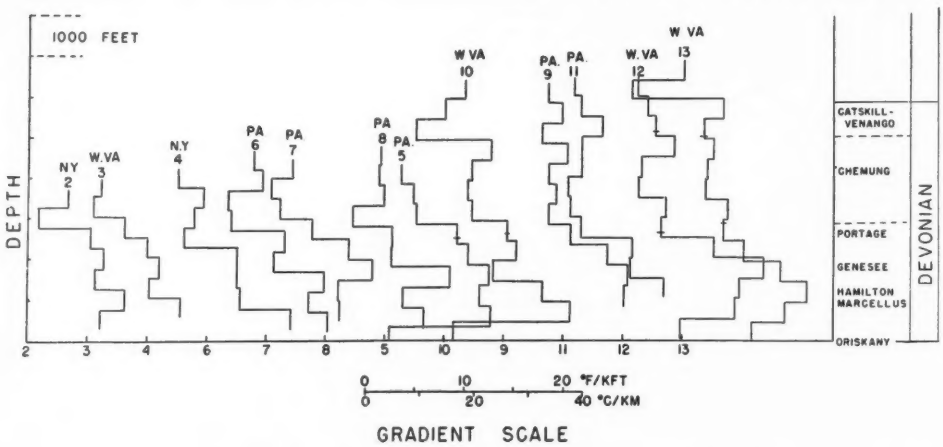


FIG. 7. Gradients for 500-foot intervals for twelve wells in the Appalachian Plateau. The numbers correspond to those of Figure 5. The sections are aligned on the Oriskany sandstone. The section shown at the right is the section for well No. 12 (see Figure 6). The numbers along the horizontal base of the diagram give the 10°C/km points for the corresponding wells.

temperature of 130°F at depths of about 6,000 feet in the Arcadia-Coon Creek field, which implies a low gradient continuing into units which *are* represented to the east. But if the lithology is, on the average, the same at the two ends of this section, and the conductivities the same, then the heat flow must be two or three times as high at the eastern end as at Oklahoma City. Most of the attempts to account for this large difference are unconvincing. McCutchin advances several tentative proposals, but only one of them seems now to have merit; this is the suggestion that circulation of ground water may be important. If, indeed, water moves generally downward in the neighborhood of Oklahoma City, and upward along the very gently rising basement surface, or within the pre-Pennsylvanian limestone formations, then we might have a qualitative explanation of the observations. A similar explanation has been advanced by Bullard and Niblett (1951) for the high values of heat flow in the Eakring region. There seem to be

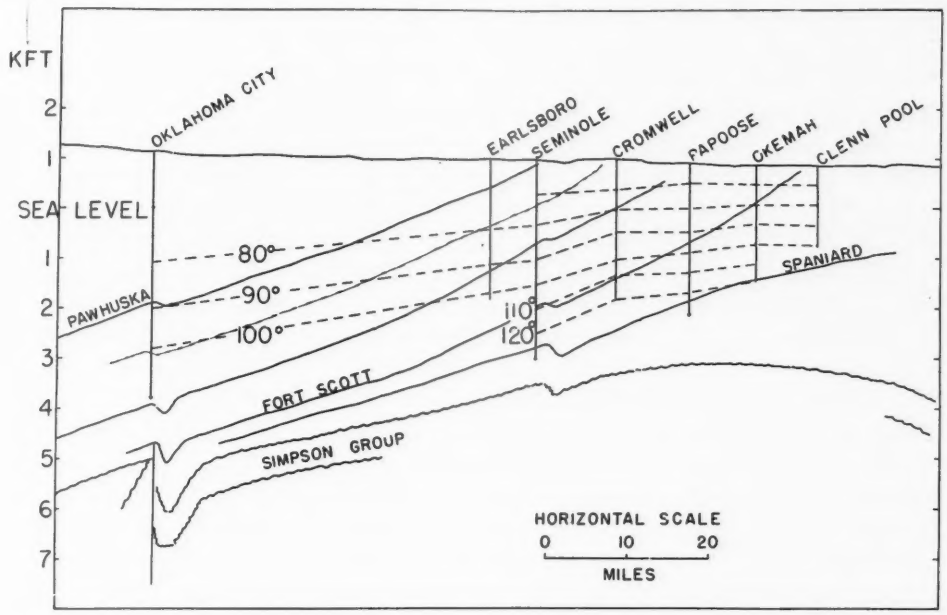


FIG. 8. Temperatures and stratigraphy east of Oklahoma City, after McCutchin and Hiestand. The broken lines are isotherms, the continuous lines are stratigraphic markers.

indications of several faults which might influence ground-water movements. The fact remains, however, that we do not know whether the conductivity varies across this region or not, and this quantity needs to be determined before the various explanations can be sorted out.

## PROPOSED ADDITIONAL INVESTIGATIONS

The older measurements present us with a number of puzzles of this kind, in nearly every case without the information regarding the properties of the rocks which is essential for interpretation. I hope that we shall be able to review much of the old work, and with the aid of studies of the lithology, and either sampling or estimates, obtain fair values of heat flow. But this is clearly a second-best approach. What is needed is an appreciation, by geologists and geophysicists working in close relation with drilling parties, of the far-reaching significance of this kind of study, and a continual watch for new opportunities.

Wherever reasonably thick sections are cored there is the possibility of a study of heat flow. The temperatures must be determined over the cored interval, and the disturbance due to drilling must either be allowed to subside or be determined. The time required for a close return to the initial, undisturbed temperature depends upon the method, the rate, and the total time of drilling, the size of the hole, and the thermal properties of the rocks. Some estimates have been given by Bullard (1947), but there is a serious need for further studies, both theoretical

and observational. Preliminary estimates suggest that the gradient of temperature in at least some intervals of rapidly drilled wells may be relatively little disturbed. On the other hand, it may turn out that wells that have been plugged with a view toward future deepening will prove most suitable, when reopened, if adequate cores have been taken and preserved. A very deep well is not required. The rise of temperature in a 500-foot interval is usually from 5 to 10°F and measurements to 0.1° are not extraordinarily difficult. An accuracy of several percent in the gradient seldom needs to be exceeded, since the mean thermal resistivity of the section will rarely be as well determined. The minimum number of samples depends upon the nature of the section: if there are many thin beds of different properties, then more are needed than in a relatively massive, uniform section.

Evidently the various requirements for good determinations of heat flow will very rarely be realized, but if one dry hole in a thousand could be utilized for such studies, our knowledge of this fundamental quantity would soon catch up with the present demands of theory, and the possibility of relating heat flow to other geological and geophysical variables might be realized. I am confident that once the desirability of such measurements is appreciated by oil geologists and geophysicists, new instruments and techniques will open up opportunities now unforeseen.

ACKNOWLEDGMENTS

I would like to record my indebtedness to Dr. Roger Revelle and Mr. A. E. Maxwell of the Scripps Institution of Oceanography for preliminary values of Pacific heat flow, to Dr. E. S. Larsen, III, and Mr. H. C. Spicer of the U. S. Geological Survey for unpublished temperatures in the wells of the Appalachian Plateau, and to Dr. Charles W. Oliphant of Tulsa for helpful discussion of the Pennsylvanian section in eastern Oklahoma.

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GEOPHYSICS, VOL. XIX, NO. 4 (OCTOBER, 1954), PP. 660–683, 22 FIGS.

# CROSS-CORRELATION FILTERING*

HAL J. JONES† AND JOHN A. MORRISON†

## ABSTRACT

Correlation analysis techniques may be applied to seismic data already subjected to standard recording and analysis procedure in an effort to extract additional information, or to raw data as an alternative filtering method. These techniques involve determination of certain parameters which provide a quantitative measure of the correlation between two sets of data. Among the most useful of these parameters are the auto- and cross-correlation coefficients and functions long used by statisticians in time series analysis and recently applied to filtering and prediction problems in the field of communications. This paper discusses some applications of correlation analysis in interpretation of seismograms. The use of cross-correlation analysis to identify weak reflections masked by high noise is illustrated for several problems. Equivalence of correlation analysis procedures to filtering operations is stressed. Special analog computing equipment facilitating computation of correlation coefficients and power spectra directly from oscillograms or graphs is described. A brief discussion of modern optimum filter theory is presented.

## INTRODUCTION

An important result of the recent intensive work in information theory (Stumpers, 1953) has been the application of auto- and cross-correlation analysis to a variety of physical problems. By way of example, auto-correlation has been applied to time series as a means of detecting hidden periodicities (Lee, Cheatham, and Wiesner, 1950), and cross-correlation finds widespread use as a method of determining the amount of coherence between two or more sets of physical measurements (Hunt, 1951; Davis, 1953). In these applications correlation analysis acts as a generalized linear filtering operation.

This paper discusses some of the early results obtained in an investigation of possible applications of correlation analysis to seismic exploration data. Since automatic computing methods are essential to the rapid, routine application of correlation methods, a considerable part of the investigation has been devoted to development of a suitable correlator for seismic problems, and a brief discussion of a two-channel analog correlator is included. This discussion is primarily concerned with analysis of conventional paper seismograms; however, the methods outlined are applicable to data in a wide variety of forms. Mathematical details are available in the numerous references cited and have been minimized in this paper.

## OPTIMUM FILTER THEORY

Since correlation analysis is a smoothing or filtering operation and since filter theory concepts are more familiar to the operating geophysicist than statistical

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correlation, a brief discussion of seismic filtering problems provides a good starting point. A great deal of attention has been devoted in recent years to the problem of designing an optimum filter to discriminate between a desired signal or "message" and background noise (see, *e.g.*, Zadeh, 1953*a*). The criteria specifying an optimum filter will, of course, depend upon the particular problem. In the simplest seismic problem the message (reflections) and background noise, described in familiar energy-frequency spectrum terms, are concentrated in distinct frequency bands as shown in Figure 1, and a not-too-carefully designed band-pass filter will be near-optimum. In the more difficult problem of Figure 2, reflection and noise spectral bands overlap, and one must make a decision on how

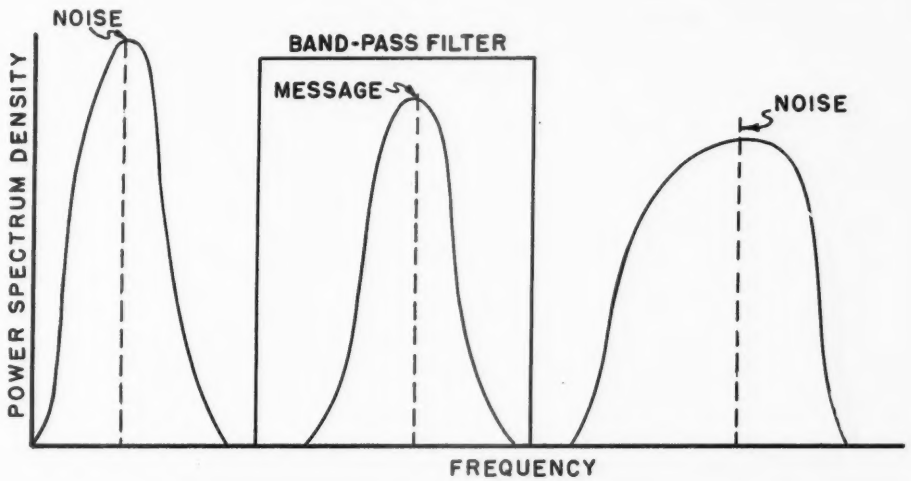


FIG. 1. Message and noise power spectra for simple seismic filtering problem.

much noise must be accepted and how much reflection energy must be rejected to achieve optimum discrimination.

The problem may be approached from two somewhat different points of view (Zadeh and Ragazzini, 1952).

1. An *extraction* filter may be designed to recover or extract the message from a message-noise complex with minimum message distortion. A suitable criterion for this problem involves minimization of the r.m.s. difference between actual filter output and message. This problem has been investigated, for example, by Wiener (1949) and Bode and Shannon (1950) for linear filters, by Booton (1952) for time-varying linear filters, and by Zadeh (1953*b*) for some non-linear filters. These workers arrive at integral equations relating optimum filter characteristics and statistical probability distributions describing message and noise. The mathematics involved is formidable. However, optimum filters often can be closely

approximated by fairly simple apparatus, for example by delay line filters (Zadeh, 1953*b*).

2. A *pre-detection* filter may be designed to increase the possibility of detecting the presence of the message in the filtered output. A useful criterion for this problem is maximization of the reflection ($R$)-to-noise ($N$) amplitude ratio

$$R/N = \frac{\text{instantaneous peak reflection amplitude}}{\text{r.m.s. noise amplitude}}. \tag{1}$$

North (1943) has shown that when the noise is white, and Gaussian (flat spec-

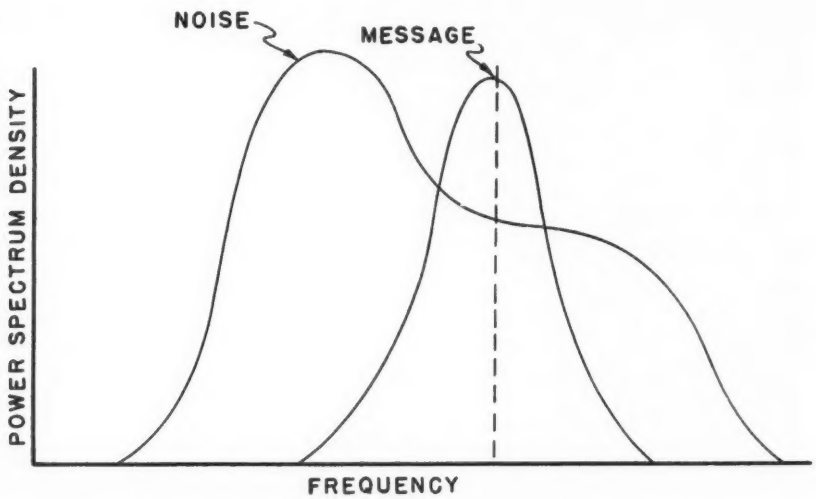


FIG. 2. Overlapping message and noise power spectra for difficult filtering problem.

trum) $R/N$ is maximized at time $t_0$ by a filter whose frequency-transfer function $Y(\omega)$ is the complex conjugate of the Fourier spectrum of $R$ or, in symbols,

$$Y(\omega) = R^*(\omega)e^{-j\omega t_0}, \tag{2}$$

where $R^*(\omega)$ is the complex conjugate of $R(\omega)$, the Fourier spectrum of $R(t) \cdot R(\omega)$ is given by

$$R(\omega) = \int_{-\infty}^{\infty} R(t)e^{-j\omega t}d\omega. \tag{3}$$

Woodward (1951) reaches the same conclusion by a purely probabilistic approach. In a later section, it will be shown that cross-correlation satisfies the North filter criterion and thus is the best linear pre detection filter for arbitrary signal waveforms mixed with white, Gaussian noise. This type of filter may, how-

ever, be far from optimum when (as is usually the case on seismograms) the noise is not "white" (Zadeh and Ragazzini, 1952). This more general problem has been treated mathematically by various authors (Dwork, 1950) and, briefly, the optimum filter transfer function is of the form

$$Y(\omega) = R^*(\omega)e^{-j\omega t_0}/N(\omega)^2. \tag{4}$$

$N(\omega)^2$ is the noise power spectrum, i.e. the filter must compensate for high power bands in the noise, as our intuition would suggest *a priori*. Precise determination

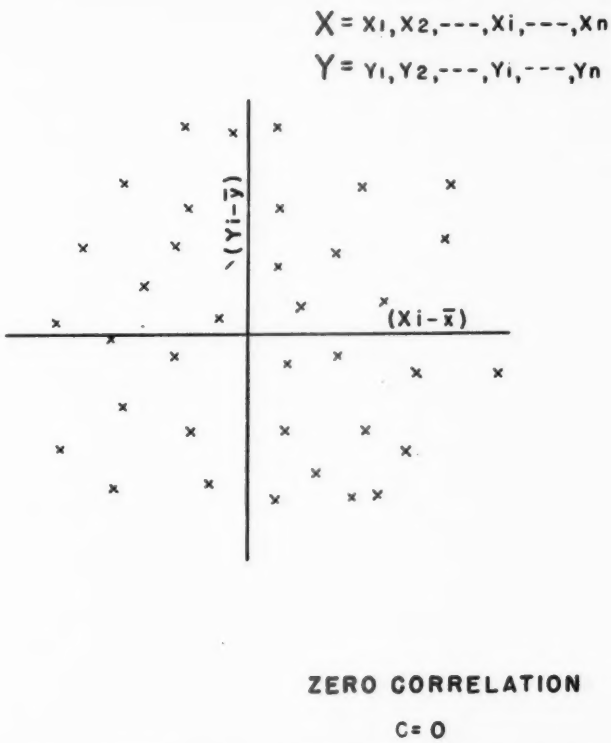


FIG. 3. Typical scatter diagram illustrating zero correlation.

of the optimum filter in a non-white noise problem is a tedious, complicated affair, beyond the scope of this paper. Our approach is simply to use cross-correlation as a pre-detection filter, maintaining awareness of its limitations. The filtering action obtained may be improved by passing the cross-correlator input through a band-rejection filter whose characteristics are based on any information we have regarding the noise power spectrum, as equation (4) indicates.

It should be noted that in many treatments of the optimum filter problem and in this paper message and noise are described in terms of energy-frequency spectra. Pike (1952) points out that mathematical description by orthogonal

function expansions other than sines and cosines may greatly simplify the analysis in many problems.

## BASIC CORRELATION THEORY

In physical problems, one is often interested in determining the degree of coherence or *correlation* between two individual sets of measurements. For example, seismologists engaged in record picking are concerned with the correlation between seismogram traces. Considering two such traces, $x(t)$ and $y(t)$, which are

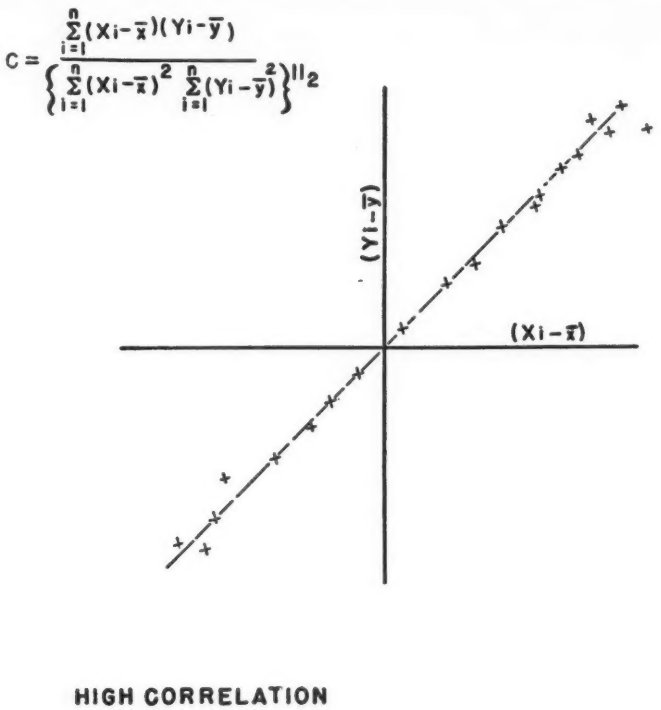


FIG. 4. Scatter diagram obtained for high linear correlation.

finite, continuous functions of time, two discrete data sequences could be formed by measuring trace amplitudes (in terms of deviations from the trace mean values $\bar{x}$ and $\bar{y}$) at regular time intervals, i.e.

$$\begin{aligned} X &= (x_1 - \bar{x}), (x_2 - \bar{x}), \cdots, (x_i - \bar{x}), \cdots, (x_n - \bar{x}) \\ Y &= (y_1 - \bar{y}), (y_2 - \bar{y}), \cdots, (y_i - \bar{y}), \cdots, (y_n - \bar{y}). \end{aligned} \tag{5}$$

If the pairs $(x_i - \bar{x}, y_i - \bar{y})$ are plotted against rectangular coordinates, the resulting *scatter diagrams* give information on the similarity of the two sequences. In the diagram of Figure 3 the points $(x_i - \bar{x}, y_i - \bar{y})$ are distributed with equal prob-

ability about the origin, and statisticians would say that the correlation between sequences was zero. In Figure 4 the points have a definite, preferred orientation along a line and are said to have a high degree of correlation. A suitable measure of correlation in this sense is the *correlation coefficient*,

$$C = \sum_{i=1}^{N} (x_i - \bar{x})(y_i - \bar{y}) \Big/ \left[ \sum_{i=1}^{N} (x_i - \bar{x})^2 \sum_{i=1}^{N} (y_i - \bar{y})^2 \right]^{1/2}. \tag{6}$$

The coefficient given by equation (6) must lie in the range $-1 \leqq C \leqq 1$, and the

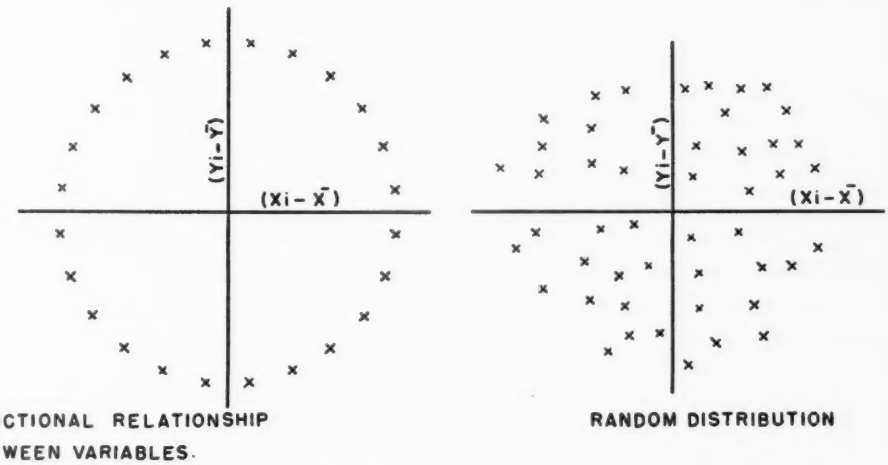


FIG. 5. Scatter diagram illustrating zero correlation for functionally related variables.

extreme values of $\pm 1$ are obtained only when the $X$ and $Y$ sets are linearly related, that is, when

$$x_i = \text{constant} + (\text{constant})\ y_i. \tag{7}$$

$C$, then, is a measure only of *linear* dependence between two sets of measurements. In fact $C$ may be zero even when the sets are functionally related as illustrated by the scatter diagram of Figure 5. Assumptions of linearity have been found to hold approximately in many physical problems, however, and thus the correlation coefficient is often useful.

Extension of the correlation coefficient concept by allowing a variable time delay, $\tau$, between the sets of measurements being compared leads to *correlation functions*. For two continuous functions of time $x(t)$ and $y(t)$, a finite *cross-correlation* function is given by

$$\phi_{xy}(\tau) = \frac{1}{T} \int_0^T x(t)y(t + \tau)dt. \tag{8}$$

An equivalent formula for discrete data is

$$\phi_{xy}(K\tau) = \frac{1}{N - M\tau} \sum_{i=1}^{N-M\tau} x_i y_{i+K\tau}, \qquad K = -M(1)o(1)M, \tag{9}$$

where the subscript $i+K\tau$ denotes the amplitude of the $Y$ sequence $K\tau$ time units after the $i$th value, $\tau$ being a fixed increment of time and $K$ an integer varying from $-M$ to $M$.

If one is interested in internal dependence (*e.g.* periodicity) within a single time series, equations (8) and (9) become

$$\phi_{xx}(\tau) = \frac{1}{T} \int_0^T x(t)x(t+\tau)dt \tag{10}$$

and

$$\phi_{xx}(K\tau) = \frac{1}{N - M\tau} \sum_{i=1}^{N-M\tau} x_i x_{i+K\tau} \qquad K = o(1)M, \tag{11}$$

where $\phi_{xx}(\tau)$ is called the *auto-correlation* function of $x(t)$. $K$ need take only values from o to $M$ since $\phi_{xx}(\tau)$ is an even function.

To get some idea of the nature of the cross-correlation function, consider two harmonic signals

$$\begin{aligned} x(t) &= A_x \cos(\omega t + \theta_x) \\ y(t) &= A_y \cos(\omega t + \theta_y). \end{aligned} \tag{12}$$

If we compute $\phi_{xy}(\tau)$ over the infinite interval using a modified form of equation (8), we obtain

$$\phi_{xy}(\tau) = \frac{A_x A_y}{2} \cos(\omega\tau + \theta_x - \theta_y), \tag{13}$$

so that cross-correlation preserves information about amplitude of the common frequency of $x(t)$ and $y(t)$ and about the phase angle difference of this frequency.

The correlation functions contain the same information as the more conventional energy-frequency spectra. To illustrate this, consider an arbitrary function $x(t)$ defined over the interval $o \leqq t \leqq T$ and zero outside this interval. The Fourier spectrum of $x(t)$ is given by

$$X(\omega) = \int_{-\infty}^{\infty} x(t)e^{-j\omega t}dt, \tag{14}$$

where $x(t)$ is given by the Fourier transform mate of equation (14) as

$$x(t) = \frac{1}{2\pi} \int_{-\infty}^{\infty} X(\omega)e^{j\omega t}d\omega. \tag{15}$$

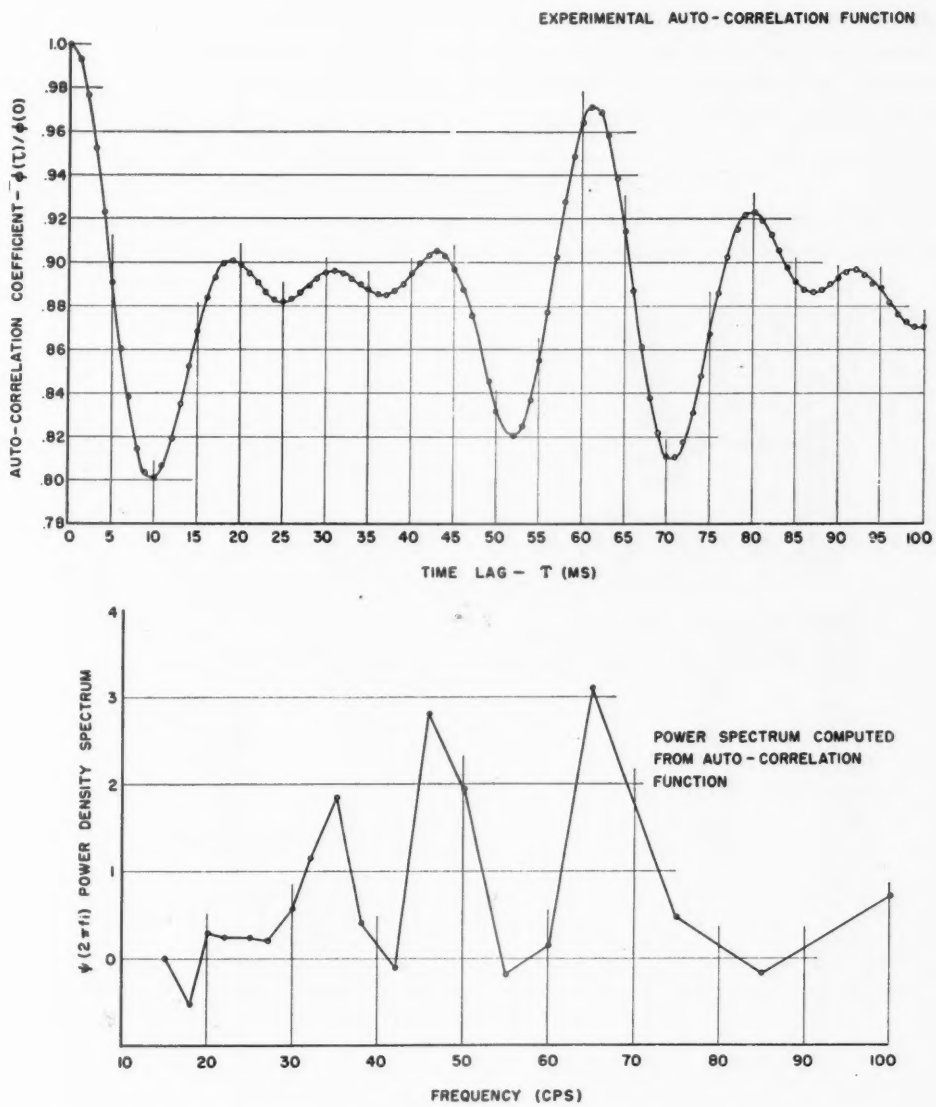


FIG. 6. Illustration of relationship between auto-correlation function and power spectrum.

The spectrum and finite auto-correlation function are related by the following equation

$$\phi_{xx}(\tau) = \frac{1}{T}\int_{-\infty}^{\infty} |X(\omega)|^2 e^{-j\omega\tau} d\omega. \tag{16}$$

$|X(\omega)|^2$ is called the energy-frequency spectrum of $x(t)$ and $|X(\omega)|^2/T$ is an

approximate power spectrum of $x(t)$. Thus one can use the auto-correlation as a means of determining the energy-frequency spectrum of a disturbance, as illustrated in Figure 6 for an auto-correlation function computed from a one-second interval of a seismogram with strong water-layer multiple reflections.

## COMPUTING EQUIPMENT FOR CORRELATION ANALYSIS

The computations required to determine correlation functions involve multiplication of paired values of two inputs and accumulation of the resulting prod-

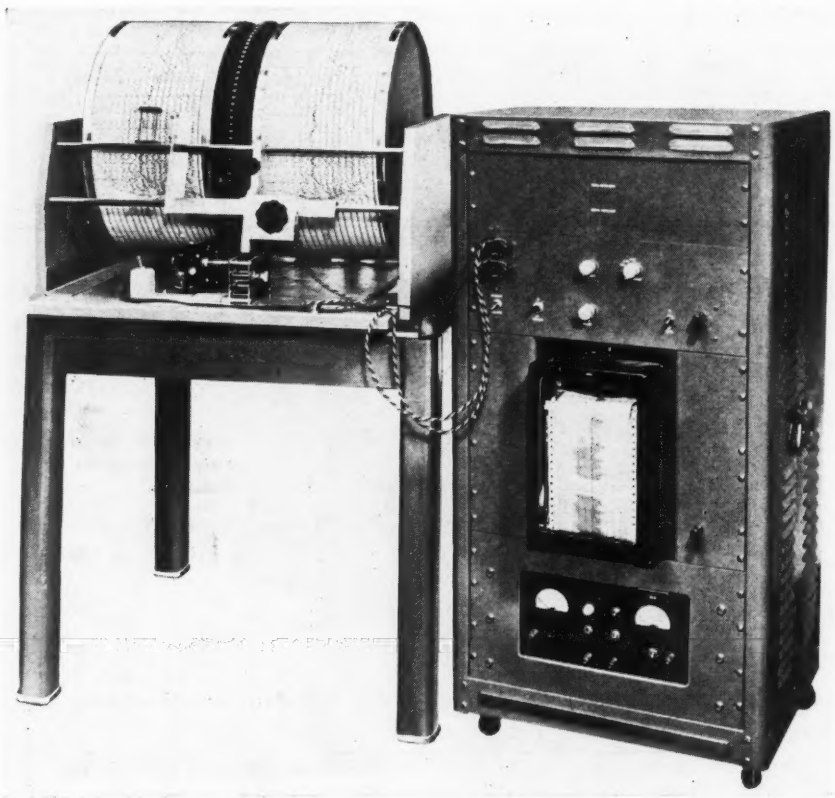

FIG. 7. Two-channel analog seismic correlator with curve-tracer input.

ucts over finite time intervals as expressed by equations (9) and (11). It will be noted that computation of the energy-frequency spectra from the correlation functions—equation (16)—and direct computation of the spectrum by means of a Fourier expansion (see, *e.g.*, Cuccia, 1952) require similar computational procedures, with one input being a sine or cosine function.

Typical computations may require a large number of multiplications, hence the utility of automatic computing equipment is clear. General purpose digital

computers would be quite suitable; however, since field data originally are in analog form, a conversion to digital form is required. Unless suitable analog-to-digital converters are available, this conversion may be tedious and time consuming. It would appear, then, that analog equipment capable of handling input data in forms commonly used in seismic exploration (*e.g.* paper oscillograms and magnetic recordings) would have definite value.

The specific correlator described here is a two-channel analog machine provided with a curve tracer input stage. Basic design specifications for this correlator were as follows:

1. Provision of a curve tracer to permit computation directly from paper records and graphs.

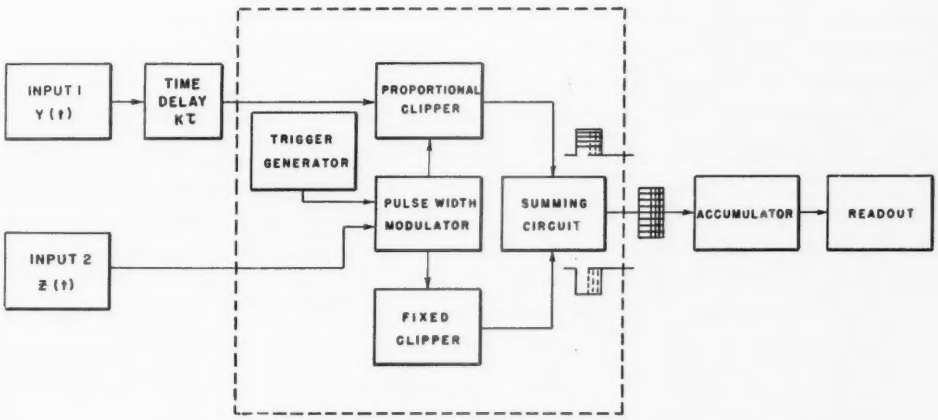


FIG. 8. Block diagram of two-channel analog seismic correlator.

2. Means of introducing relative time delay between two inputs and of varying this delay in small increments.
3. An analog multiplier permitting high speed multiplication of two continuous inputs and suitable for use with a variety of inputs, including magnetic recordings.
4. Means of accurately accumulating a large number of products.
5. Provision for read-out of computed values.

Figures 7 and 8 are, respectively, a photograph and block diagram of the equipment. The curve tracer consists of two identical drums mounted on a common shaft. Clutch mechanisms permit introduction of variable time delay accurately in 2.5-millisecond or larger increments by rotating the drums. The drums are driven by a synchronous motor and chain-sprocket drive, with a gear train permitting selection of five drum speeds. The present curve-tracing mechanism consists of a manually-controlled pointer on each drum. The inputs being correlated are fixed on the drum surfaces, and operators follow the traces by turning a knob, ganged to the pointer and a linear potentiometer. Voltages de-

veloped across the potentiometers are proportional to trace amplitudes. Multiplication is accomplished by a pulse area method. One input is sampled at regular time intervals, and the output of the pulse width modulator is, then, a train of equally spaced pulses whose durations are proportional to trace amplitude at the sampling instants. A proportional clipper block continuously clips these pulses at heights proportional to the second input, so that the areas of the resulting pulses are proportional to the products of the input (Cheatham, 1950; Singleton, 1950). These pulses are fed to a Miller-type integrator with the time constant of the integrator chosen to guarantee accurate accumulation over the times encountered in practical problems. Present read-out mechanisms include a pen recorder and a vacuum-tube voltmeter.

The approximate high frequency cut-off of the system is determined by the effective sampling interval, which can be made very high compared to the upper limit of the seismic band, and by minimum lag increments available; for example, lag increments of 2.5 milliseconds impose a cut-off at about 200 cps in the correlation computations. The low frequency cut-off, and hence the resolution of frequencies, depends upon the length of the time sample ($N-M\tau$ time units) and the maximum time lag used ($M\tau$). Greater resolution cannot be obtained simply by increasing $M$, since the ratio $M\tau/(N-M\tau)$ must be kept small (1/10 or less) if reliable power spectra are to be obtained (Tukey, 1949).

## CROSS-CORRELATION ANALYSIS OF SEISMOGRAMS

Cross-correlation is an effective means of separating signal from noise in certain types of problems. To illustrate this, consider two seismogram traces, each consisting of an additive mixture of reflections and noise, such that

$$\begin{aligned} x(t) &= R(t) + N_x(t) \\ y(t) &= R(t) + N_y(t). \end{aligned} \tag{17}$$

The cross-correlation of $x(t)$ and $y(t)$ is given by

$$\phi_{xy}(\tau) = \frac{1}{T}\int_0^T [R(t) + N_x(t)][R(t+\tau) + N_y(t+\tau)]dt \tag{18}$$

or, in terms of correlation functions, by

$$\phi_{xy}(\tau) = \phi_{RR}(\tau) + \phi_{RN_y}(\tau) + \phi_{N_xR}(\tau) + \phi_{N_xN_y}(\tau). \tag{19}$$

$\phi_{xy}(\tau)$ is, then, a linear combination of four correlation functions. If the total time interval is large, the chief contribution to $\phi_{xy}(\tau)$ will be made by the noise correlation term $\phi_{N_xN_y}(\tau)$ hence a plot of $\phi_{xy}(0)$ versus seismometer spacing (such as Figure 9) may be used to choose the minimum spacing for which compositing of seismometer outputs will effect useful cancellation of noise. If spacings are properly chosen, noise correlation will be small and equation (19) may be written as

$$\phi_{xy}(\tau) = \phi_{RR}(\tau) + \phi_{RN_y}(\tau) + \phi_{N_xR}(\tau). \tag{20}$$

If some knowledge of reflection waveform is available, equation (20) reduces to the following simple equation, letting $x(t) = R(t)$ and $N_y(t) = N(t)$,

$$\phi_{xy}(\tau) = \phi_{RR}(\tau) + \phi_{RN}(\tau). \tag{21}$$

A possible procedure for applying cross-correlation analysis to reflection seismograms may, then, be outlined as follows:

1. Select an approximate reflection waveform—this may be from a good trace, a good record, or a record from a nearby good area.

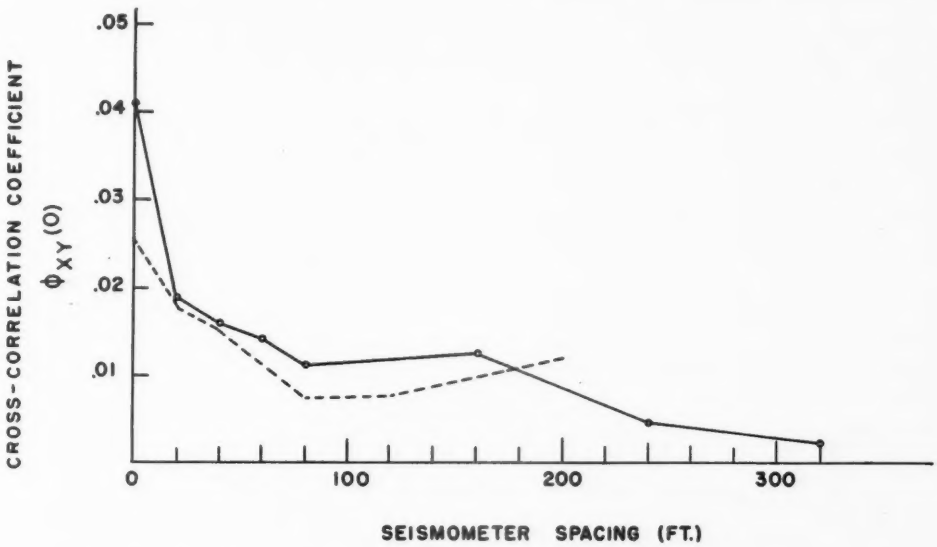


FIG. 9. Zero-lag cross-correlation between one-second intervals of two seismogram traces vs. seismometer spacing, Buckner area, Dallas County, Texas.

2. Cross-correlate the approximate reflection waveform versus a "noisy" trace, obtaining $\phi_{xy}(o)$ at evenly spaced time points. The computation interval for each point is the reflection duration.
3. Plot the cross-correlation versus time, forming a *correlogram*. Positive peaks in the correlogram occur when trace-reflection correlation is high, *e.g.*, when $R(t)$ occurs in the trace. Maximum peaks will occur at the beginning of $R(t)$ in the trace.

The procedure is illustrated in Figure 10.

Cross-correlation analysis of this type is a linear filtering operation in which the filter characteristics are determined by the expected signals. To demonstrate this we discuss the cross-correlation in spectral terms.

The cross-correlation will be zero outside some interval $-T' \leqq \tau \leqq T'$ and may

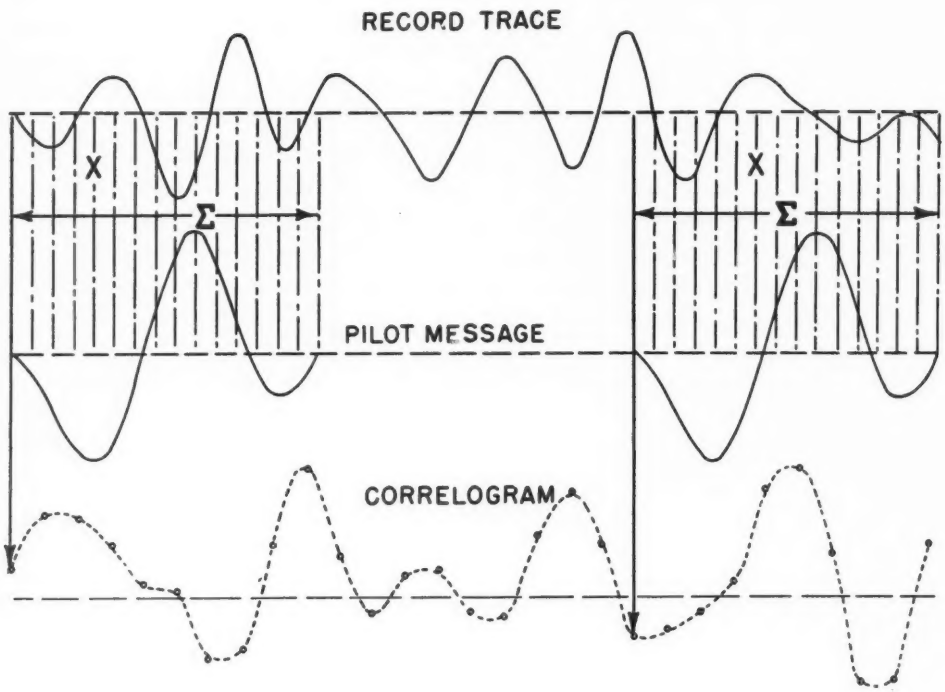


FIG. 10. Graphical illustration of pilot-message cross-correlation method.

be expressed in Fourier integral form as

$$\phi_{Ry}(\tau) = \frac{1}{2\pi}\int_{-\infty}^{\infty}\Phi(\omega)e^{j\omega\tau}d\omega. \tag{22}$$

$\Phi(\omega)$ is the spectrum of $\phi_{xy}(\tau)$ and is given by the inverse Fourier transform as

$$\Phi(\omega) = \int_{-\infty}^{\infty}\phi_{Ry}(\tau)e^{-j\omega\tau}d\tau \tag{23}$$

$$\Phi(\omega) = \int_{-\infty}^{\infty}e^{-j\omega\tau}d\tau\int_{-\infty}^{\infty}R(t)y(t+\tau)dt. \tag{24}$$

Equation (24) can be rewritten as

$$\Phi(\omega) = \int_{-\infty}^{\infty}R(t)e^{j\omega t}dt\int_{-\infty}^{\infty}y(S)e^{-j\omega S}dS, \tag{25}$$

writing $S=t+\tau$. In terms of spectra, equation (25) becomes

$$\Phi(\omega) = R(-\omega)\cdot Y(\omega), \tag{26}$$

where

$$R(-\omega) = \int_{-\infty}^{\infty} R(t)e^{+j\omega t}dw$$

$$Y(\omega) = \int_{-\infty}^{\infty} y(t)e^{-j\omega t}d\omega.$$

Now, since $R(t)$ is real, we can write

$$R(-\omega) = R^*(\omega)$$

and

$$\Phi(\omega) = R^*(\omega) \cdot Y(\omega), \tag{27}$$

where $R^*(\omega)$ is the complex conjugate of $R(\omega)$. Equation (27) tells us that cross-correlation is equivalent to passing the trace $y(t)$ through a filter whose complex frequency transfer function is the complex conjugate of the reflection itself.

The energy in a particular frequency band $\omega - d\omega$ to $\omega + d\omega$ can be estimated by

$$E(\omega) = | \Phi(\omega) |^2, \tag{28}$$

so that we have

$$E(\omega) = | R^*(\omega) |^2 | Y(\omega) |^2. \tag{29}$$

Cross-correlation, then, has a transfer function whose amplitude portion is simply the amplitude spectrum of the approximate reflection. Since the phase portion is the image of the reflection phase characteristic, the effect is to bring all common Fourier components of $y(t)$ and $R(t)$ in phase at a point corresponding to the beginning of $R(t)$ in the trace $y(t)$. The output reflection waveform is simply the auto-correlation of the input waveform. The process of correlating an expected waveform against an arbitrary input is directly comparable to use of a linear operator of the type used by workers at MIT (Wadsworth et al., 1953). The constants in the linear operator of the form

$$\text{output} = \sum_i (a_i) \cdot (\text{input})$$

are simply the amplitude values of the pilot waveform which multiply the input amplitude values (cf. Fig. 10).

Figures 11–16 illustrate the cross-correlation filtering method. The wavelet of Figure 11 was added at two places with zero moveout to the seismogram traces of Figure 12 which constitute the noise background. The cross-correlation of $R(t)$ and each trace was computed and is shown in Figure 13, and the reflection visible at 0.816 seconds in Figure 12 is clearly defined. The output reflection

waveform is shown in Figure 14 and is simply the wavelet auto-correlation. In this problem the approximate reflection was exactly the reflection. The ratio $R/N$ was taken as 1/1.5 and 1/3 for the two correlograms shown in Figures 15 and 16. The ratio varies with time and was much smaller on trace 3 for the first added wavelet. Some small differences in the correlograms of Figures 15 and 16 are due to different computational methods employed for the two problems. Energy-frequency spectra for wavelet and noise are illustrated in Figure 17. Since there is considerable spectral overlap, this corresponds to a fairly difficult

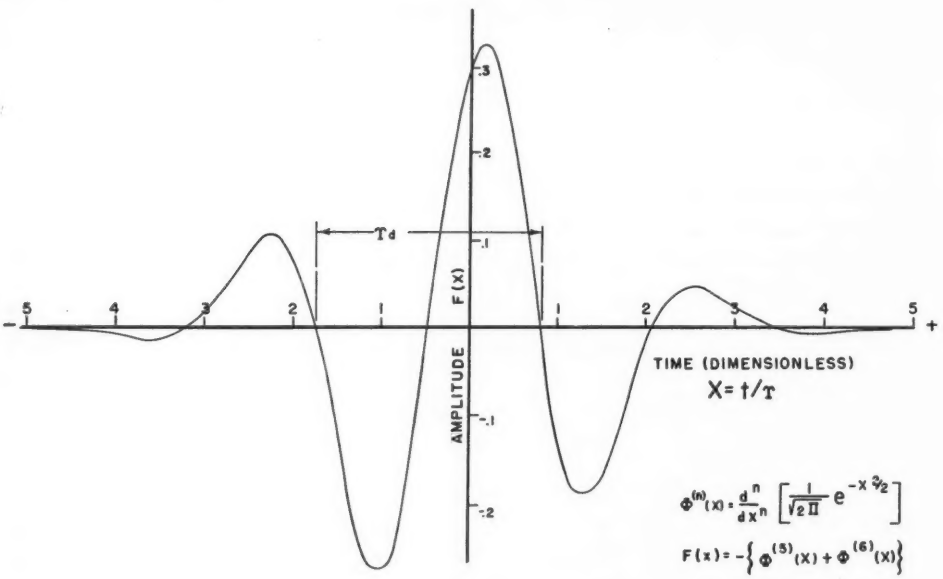


FIG. 11. Seismic pilot message used in cross-correlation analysis of Figures 13–15.

filtering problem. The filtering action of cross-correlation is shown more clearly in Figure 18 where the dominant period of $R(t)$ is varied, effectively changing the band width and central frequency of the filter, as shown by spectra in Figure 19. Figures 20–22 illustrate a more realistic problem. A reflection is marked on the downhole spread record of Figure 20. This reflection is not readily identifiable on the surface spread record obtained at the same location on the same shot (Fig. 21). The correlogram of Figure 22 was prepared by using the reflection waveform on trace 3 of Figure 20 as $R(t)$ and shows two fair lineups apparently associated with the occurrence of $R(t)$ in the surface record. This example illustrates the manner in which cross-correlation could be applied to practical problems, working from usable to NG data.

It should be noted that seismic data used for the correlation analysis discussed above were obtained with a seismic recording system using automatic gain control amplifiers and with fairly wide-band response (3 db points at 10 and 120 cps).

FIG. 12. Noise background for cross-correlation problem of Figures 13–15 (actual seismogram traces from Buckner area, Dallas County, Texas).

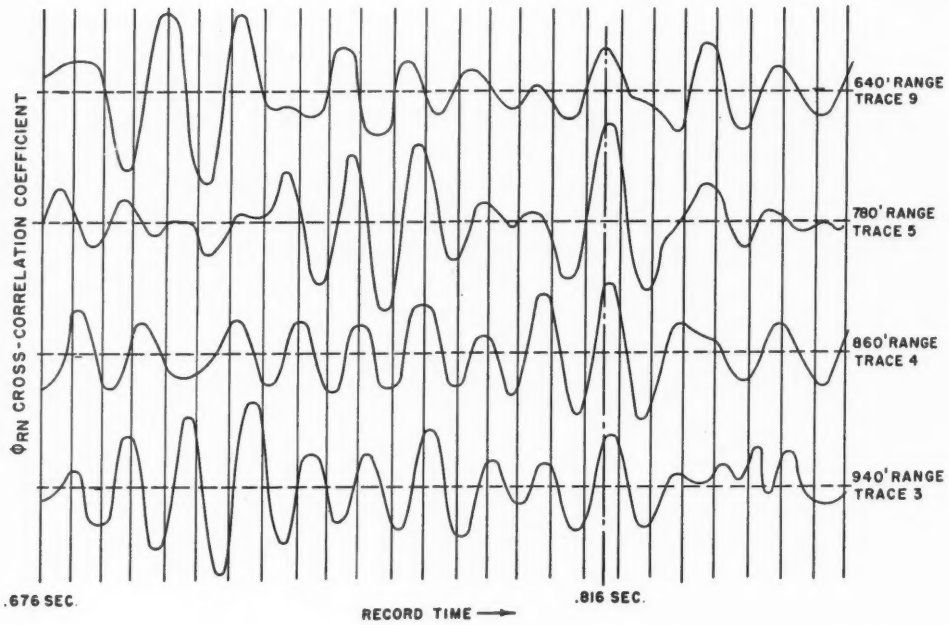


FIG. 13. Cross-correlation of pilot reflection of Figure 11 (dominant frequency=49 cps) with noise of Figure 12, showing well defined reflection at .816 seconds.

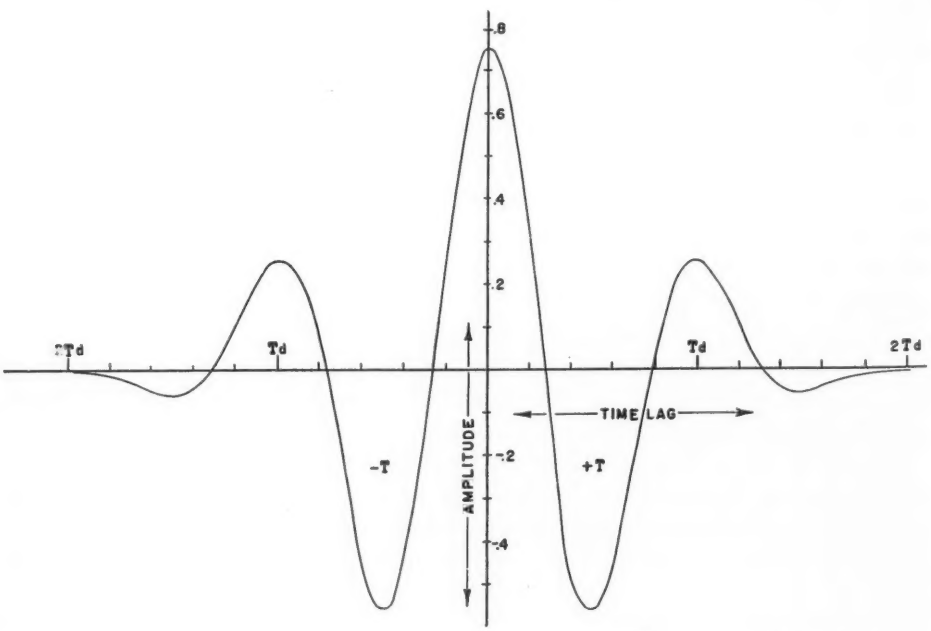


FIG. 14. Reflection waveform obtained by cross-correlation (auto-correlation of pilot reflection of Figure 11).

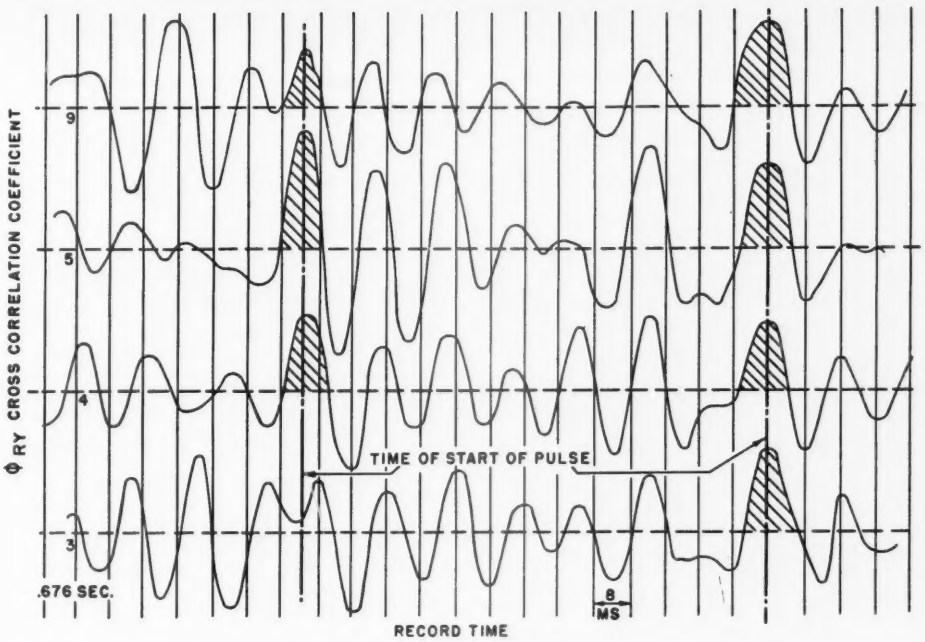


FIG. 15. Correlogram obtained by cross-correlation of pilot reflection of Figure 11 versus noise of Figure 12, with two pilot reflections added to the noise background (average R/N=1/1.25–1/1.5).

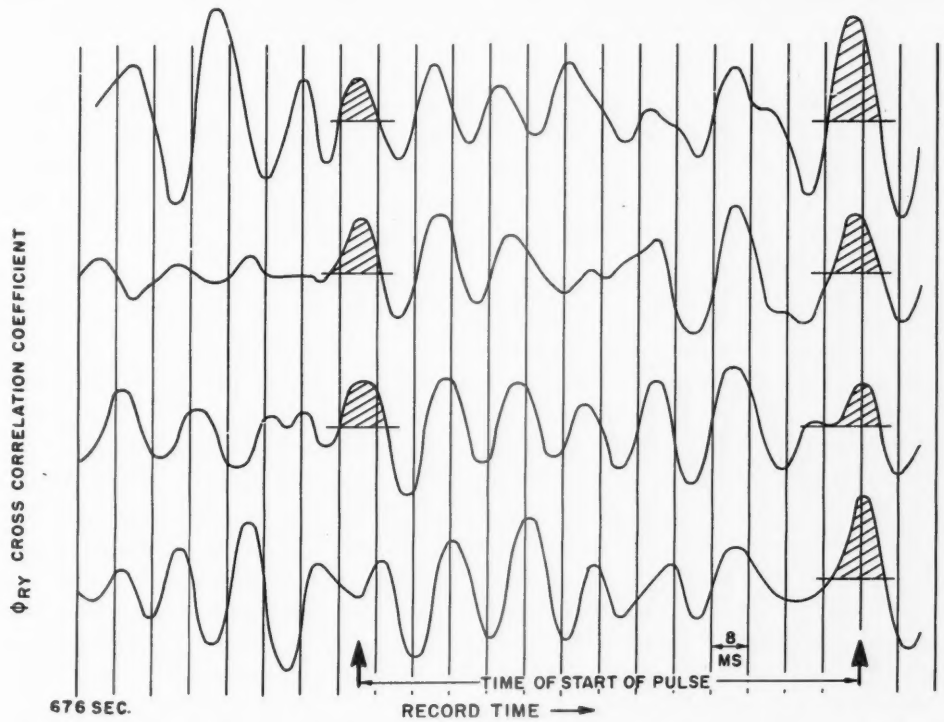


FIG. 16. Correlogram obtained by cross-correlation of pilot reflection of Figure 11 versus noise of Figure 12, with two pilot reflections added to the noise background (average R/N=$\frac{1}{2}$–$\frac{1}{3}$).

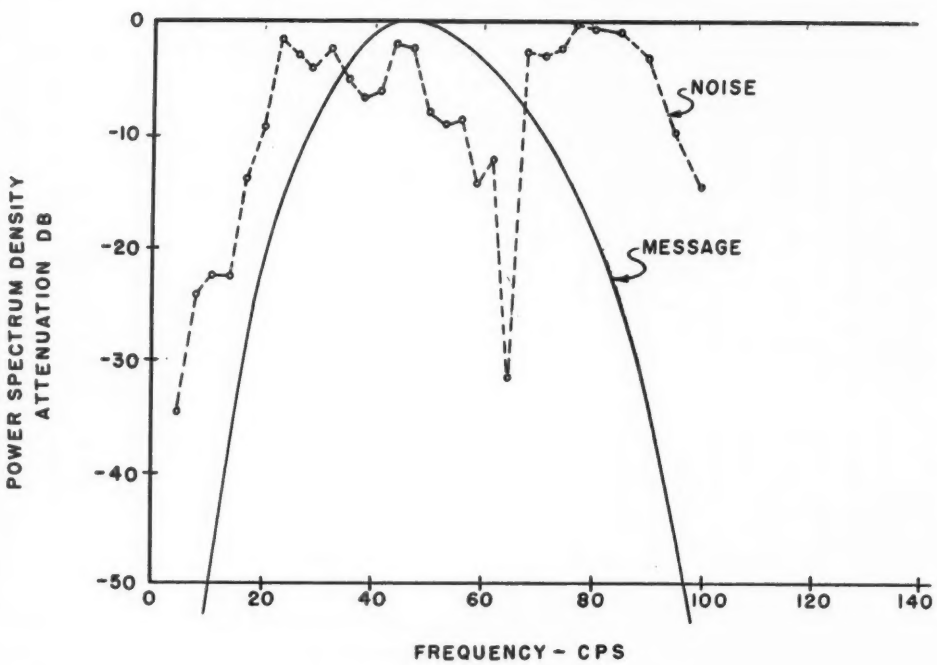


FIG. 17. Power spectra of pilot message of Figure 11 and typical trace of record from which noise of Figure 12 was taken.

Data in the form of a magnetic recording is, of course, more suitable, since a great deal more information is originally recorded. The problems presented here and the quality of results obtained are believed to be representative of practical seismic problems. More dramatic illustrations of enhancement of message discrimination by correlation analysis could, of course, be given for specially selected problems.

## REMARKS

Correlation analysis may be regarded as an alternative method of linear filtering, utilizing the time-amplitude properties of signal and noise. Since the correlation representation is uniquely related to conventional energy-frequency spectra, one can expect the technique to produce results comparable to those obtained with linear electric wave filters. Auto-correlation can be used to separate periodic signals from non-periodic noise backgrounds, but acts as a passive filter of rather low selectivity (Goldman, 1953, chapter 7). Cross-correlation has some advantages as a linear pre-detection filter. The filter characteristics are determined by the signal one expects. Further, for noise whose spectrum is broad and reasonably flat, a cross-correlator may be the best linear pre-detection filter. Clearly, sharp-cutoff filters cannot be obtained by cross-correlation over short time intervals. Cross-correlation also is sensitive to phase coherency as well as

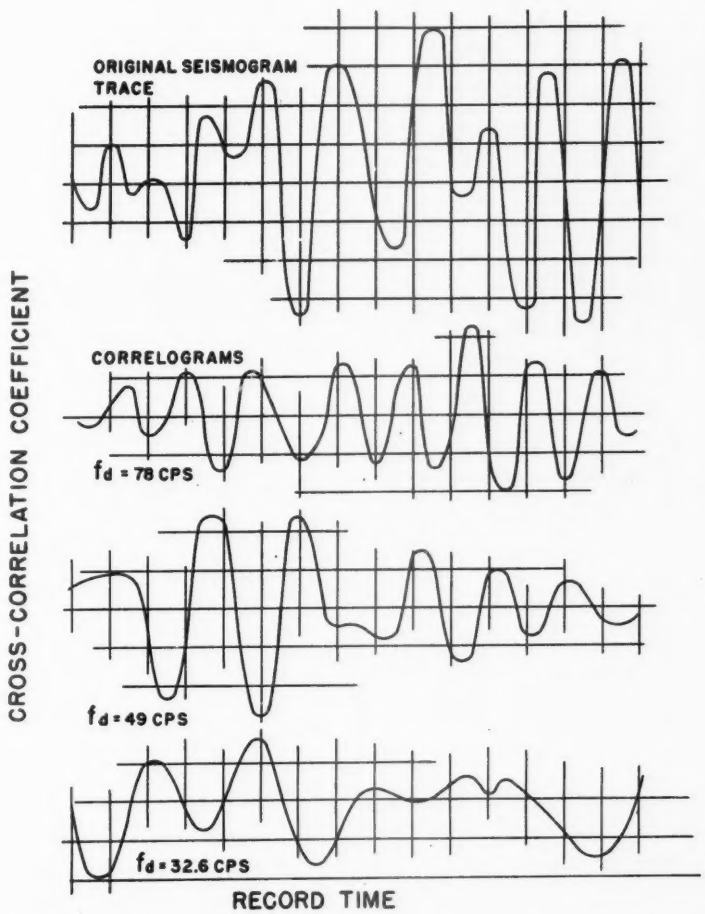


FIG. 18. Correlograms of seismogram trace for different dominant frequencies of pilot message, illustrating filtering effect of cross-correlation.

amplitude coherency between disturbances and is a useful measure of trace-to-trace coherency. The limitations of the method are, however, clear. The ideal situation of narrow band signals in broad band noise is not common in reflection problems. Often noise seems to consist of a complex of reflection-like wavelets, and, so far as a single trace is concerned, cross-correlation (and wave filters) will be unable to separate wavelets of similar spectra. Some improvement is, of course, obtained by making use of the characteristic phase relationships of reflections from trace to trace. In fact, an optimum pre-detection filter for reflection work must make use of this powerful criterion. Another disadvantage is that the equipment required is reasonably complex and expensive. A multi-channel analog correlator is, however, a feasible field instrument and would operate most effectively in conjunction with the playback of a reproducible recording system. To be of

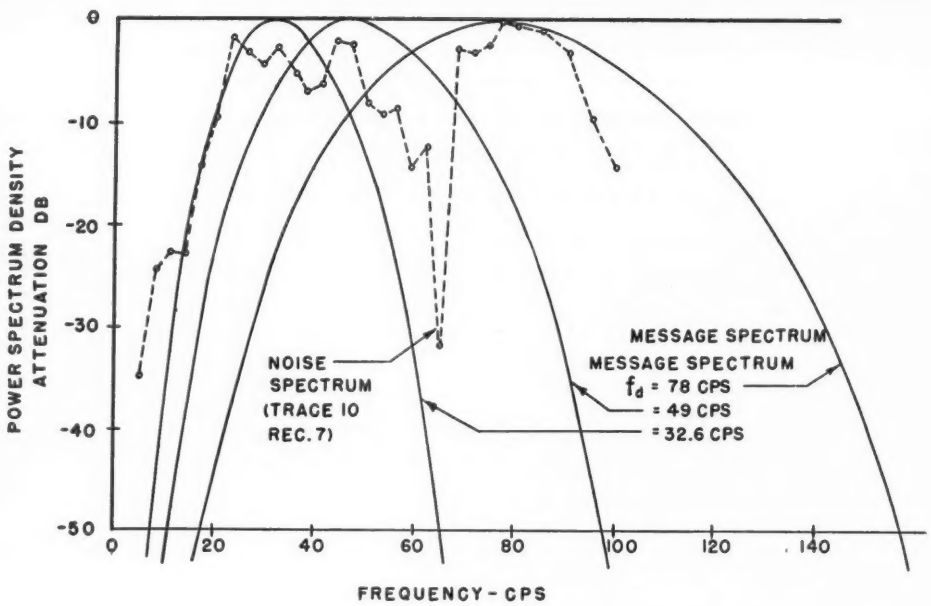


FIG. 19. Power spectra of pilot messages and noise (seismogram trace) of Figure 18.

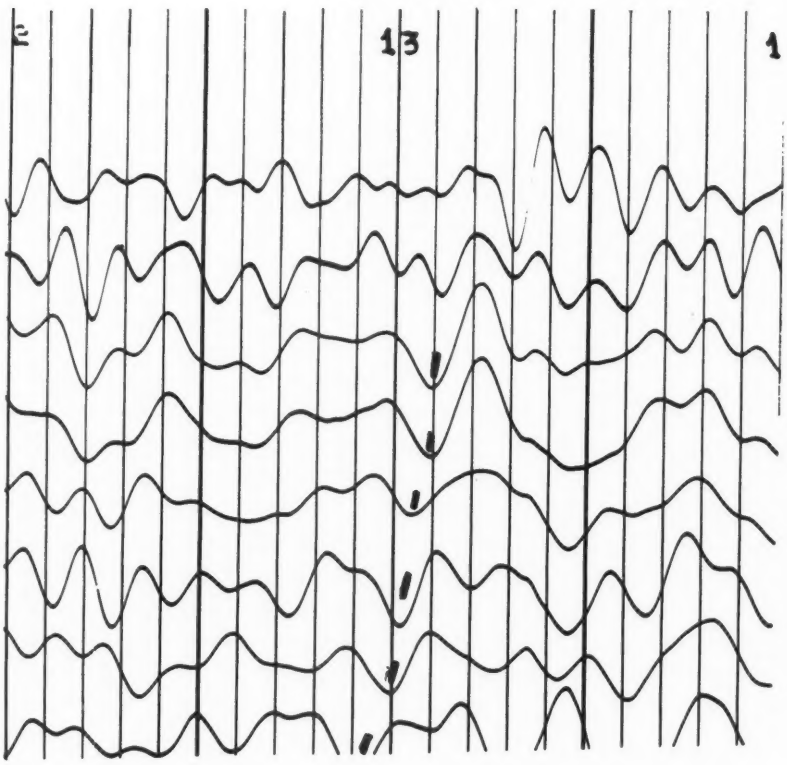


FIG. 20. Subsurface vertical spread (seismometers clamped in hole at 10, 25, 50, 75, 125, and 175 feet) Buckner area, Dallas County, Texas, showing clear reflection.

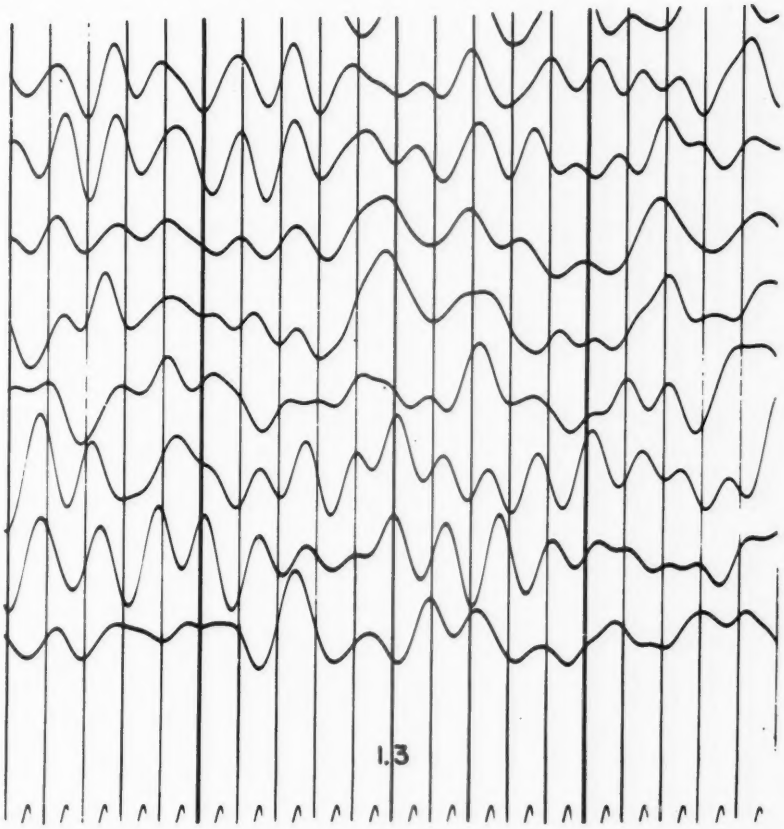


FIG. 21. Surface seismic record obtained from same shot as subsurface record of Figure 20, showing no definite reflections.

practical use, the correlator should be capable of filtering an entire trace or group of traces in a one-pass, continuously-recording operation. In summary, correlation analysis promises to be a useful special analysis tool capable of adaption to field use with modern magnetic recording equipment. The value of this tool as compared with conventional filtering techniques can only be determined by applying both methods to the same data in a large number of problems.

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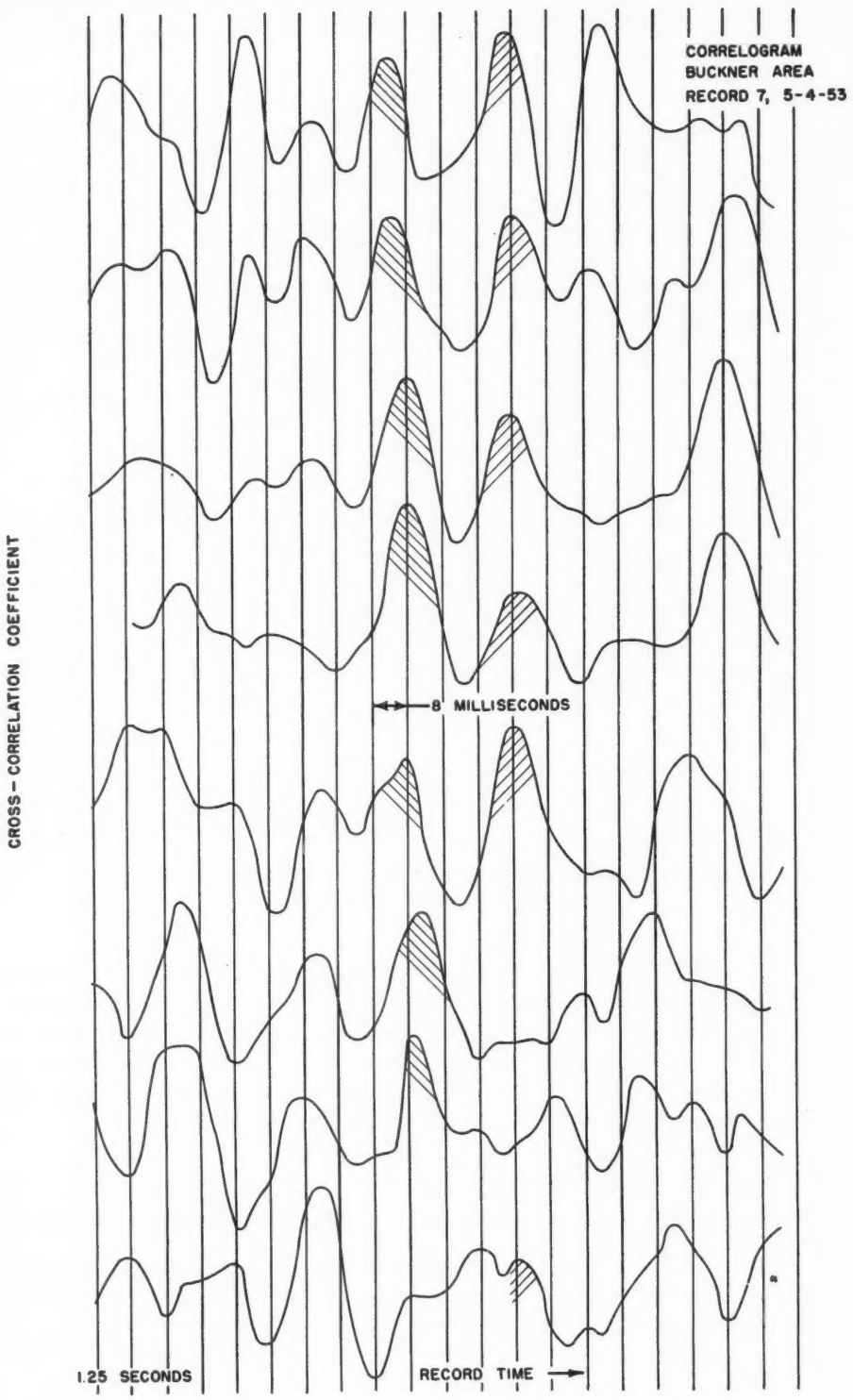


FIG. 22. Correlogram obtained using reflection waveform of trace 3, Figure 20 as pilot message, and Figure 21 as noise-message complex, showing two fair lineups.

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GEOPHYSICS, VOL. XIX, NO. 4 (OCTOBER, 1954), PP. 684–694, 7 FIGS.

# REFLECTION QUALITY, A FOURTH DIMENSION*

BEN F. RUMMERFIELD†

## ABSTRACT

The quality of seismic reflection results has a direct relation to newer petroleum provinces in the North American continent. An approach is suggested whereby a seismic study of changes of physical characteristics of subsurface reflecting horizons and/or reservoir beds can be attempted. The changes in the quality of deeper reflecting horizons in relation to a persistent shallow or "control" horizon may be able to add a fourth dimension to present seismic interpretations. It is possible that every record may become important from the viewpoint of evaluating petroleum possibilities and not merely those records "on structure."

## INTRODUCTION

A generalized study has been made of the quality of seismic data throughout the North American continent. The coincidence of oil-producing zones and areas of fair-to-good seismic results suggests that the ability to obtain favorable seismic data has had a marked influence upon the discovery of new oil fields.

An attempt will be made to move from this broad generalization to a more specific and detailed evaluation of the quality of individual reflections on *single* seismic records and their possible relation to "oil finding." *The problem then is whether or not information other than structural can be derived from a study of seismograms.*

The ability to record satisfactory seismic data from subsurface geological beds is directly dependent upon the modulus of elasticity of the specific geological horizon concerned. Another way of saying this is that satisfactory reflections can be obtained from marker horizons which have a pronounced contrast in physical characteristics in comparison with their adjacent geological strata.

This suggests that we may have a tool whereby changes in the physical properties of a reflecting horizon may be evaluated by an analysis of the quality of individual reflections. However, certain seismic and geological control factors are essential to such a study (see cross-section in Figure 1):

1. A good, consistent shallow reflecting horizon must be present to be used as a "control horizon." This horizon is used for a quality comparison and to make certain that proper field techniques and instrumentation are being used to obtain satisfactory seismic records.

2. A deeper reflecting horizon, which is in a strategic location and/or a potential reservoir, must be present. A pronounced change in the quality of this re-

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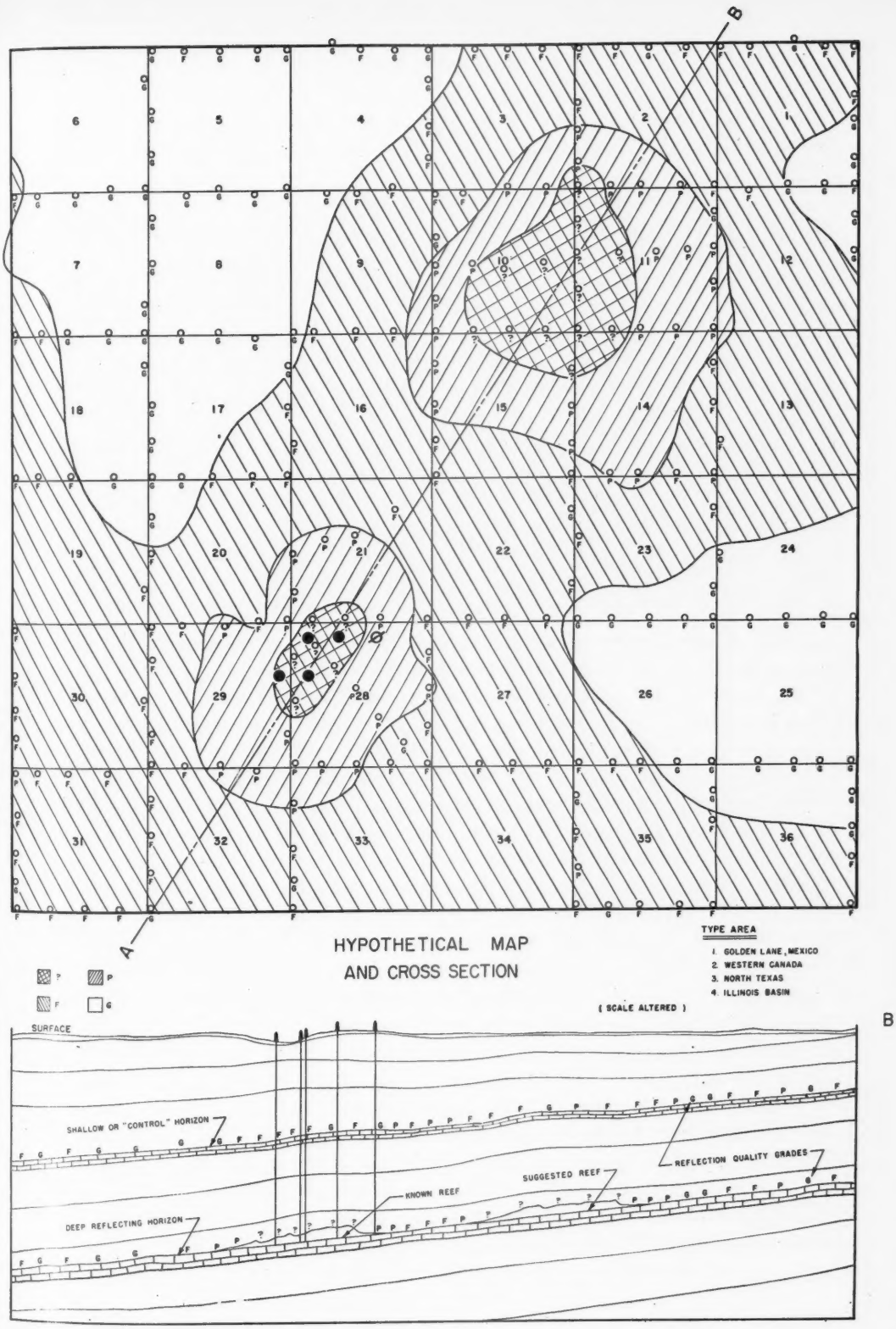


FIG. 1. Idealized cross-section showing effect of reef on reflection quality.

flection, providing the control reflection quality remains constant or nearly so, may be indicative of a change of physical characteristics within the reflecting horizon itself.

3. An even deeper reflection than the key horizon referred to in item 2 above would be helpful, though not absolutely necessary. Such a horizon would also act as an additional control horizon for quality comparison.

A map can then be prepared showing the reflecting quality at each shot point for the strategic horizon. Any changes in quality not shared by the control horizon might be used in attempting to study variations of stratigraphy or lithology.

Care must be exercised that personal feelings, which vary from day to day, do not unduly influence the judgment of the interpreter in evaluating reflection quality.

The quality of a reflection depends upon its consistency and "character"; however, quality is also a visual evaluation by the interpreter of the individual reflection. It is beneficial to choose a representative record for each area and establish a standard quality grade for reflections so as to provide a common basis for comparison.

## EXAMPLES

The diagrams which illustrate the method in this paper are simplified and hypothetical, but they approximate actual maps prepared by this method.

Figure 1 is an idealized section similar to the Western Canadian Geosyncline. The fact that we obtain fair-to-good reflections from the persistent shallow horizon assures us that our instrumentation and field technique are adequate for the area. An attempt is then made to qualify the deeper reflection.

It is apparent that the presence of a reef and concomitant changes in stratification and lithology have resulted in a decay of the reflection coefficient of the deep horizon in the immediate zone of the reefing, whereas the shallow horizon, having undergone no change in physical characteristics, continues to serve as a satisfactory reflecting, or control, horizon.

The results are evaluated by contouring a map showing the quality of the reflections obtained from the deeper horizon at each shotpoint. In our idealized case, it would be feasible to associate an area of poor-to-questionable deep reflection quality with the presence of a possible reef.

The unique photograph (Fig. 2) obtained from the Geological Survey of Canada clearly presents an actual case illustrating the presence of two small reefs formed in Devonian beds of the Canadian Rockies. The changes in lithology and stratigraphy can be easily seen. This geologic section closely approximates Figure 1, if we assume several thousand feet of overlying section.

The scale of the geologic conditions as indicated by the photograph is such that it would not be readily adaptable to seismic investigation. However, the over-all change in lithology and stratigraphy clearly illustrates conditions leading to the probable degeneration of reflection quality that would be expected in a

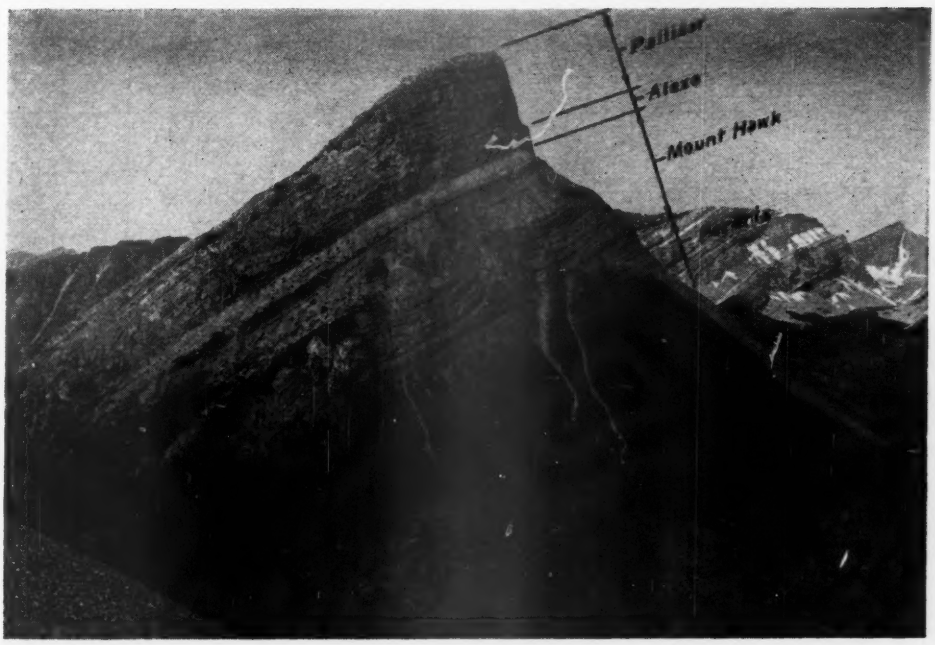


FIG. 2. Exposure of stromatolitic bioherms, Mount Hawk formation, in the Canadian Rocky Mountains. Photograph from Geological Survey of Canada.

reefing problem. It was not possible to obtain release of seismic records depicting such a problem.

Figure 3 illustrates an idealized case where seismic reflection quality degenerates gradually from good to questionable to non-existent. Such a possibility might occur where a stratigraphic pinch-out, a structural unconformity, or an erosional surface is encountered. Again, a shallower control horizon is assumed. It is believed that, by mapping the quality of the reflection used for the deeper map, it is possible to study alignments which may be indicative of old shore lines or erosional surfaces. Thus, trends such as strand line projections may be identified and valuable information may be obtained regarding subsurface structural and stratigraphic conditions.

Figure 4 is a cross-section of seismic records illustrating a loss of section in southern Oklahoma. Reflections A and B converge until the identity of reflection B is lost.

Subsurface topography may be partially outlined by a quality map study. In one area (similar to the hypothetical one shown in Figure 5) where the quality of individual deep reflections was mapped, it was found that the apparently erratic scattering of the questionable deep reflections resolved itself into a dendritic pattern that was thought to be related to a subsurface Mississippian topography. This information was very helpful, not only in placing possible reservoirs at the

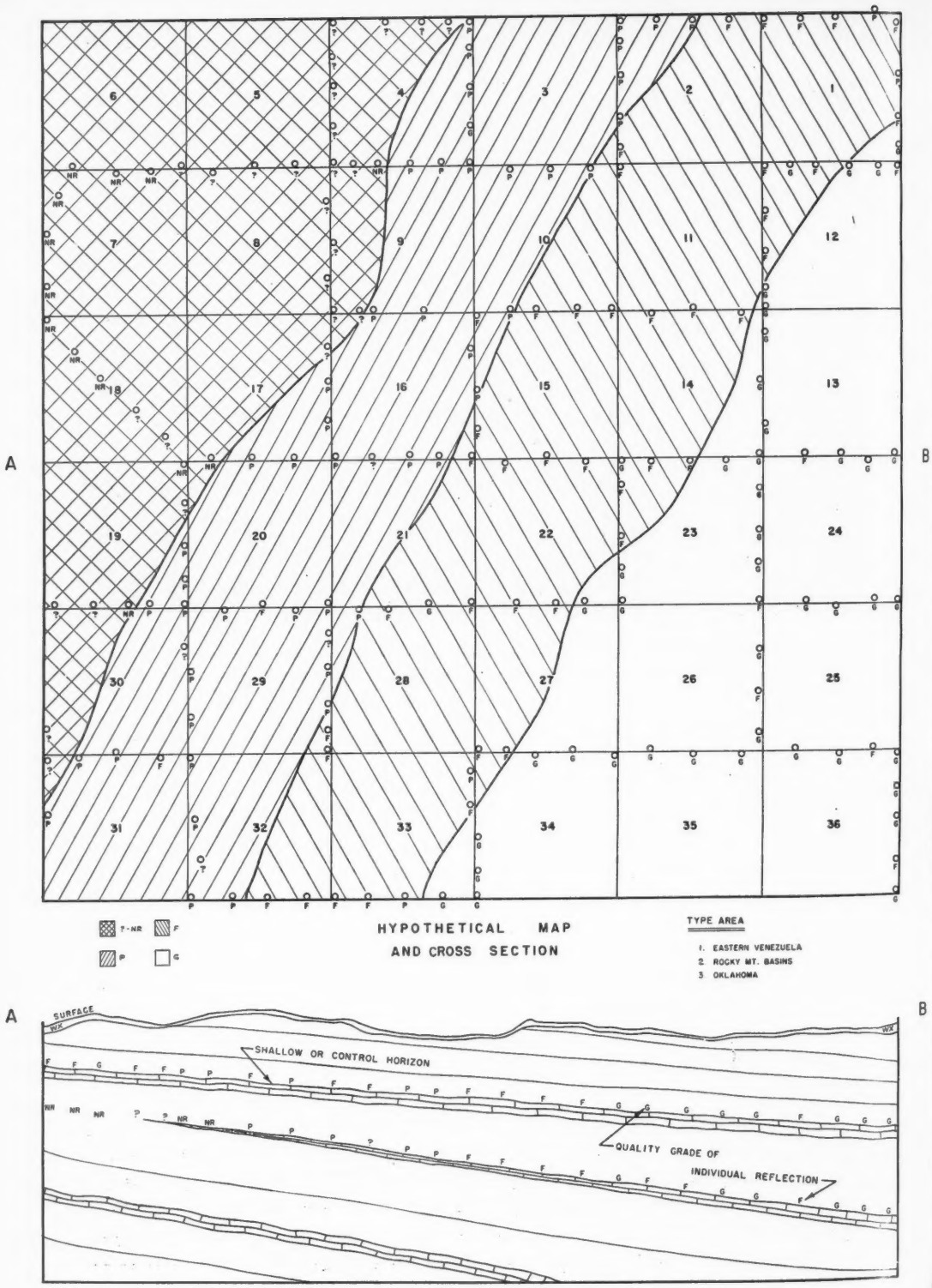


FIG. 3. Effect of pinchout on reflection quality as indicated by quality map.

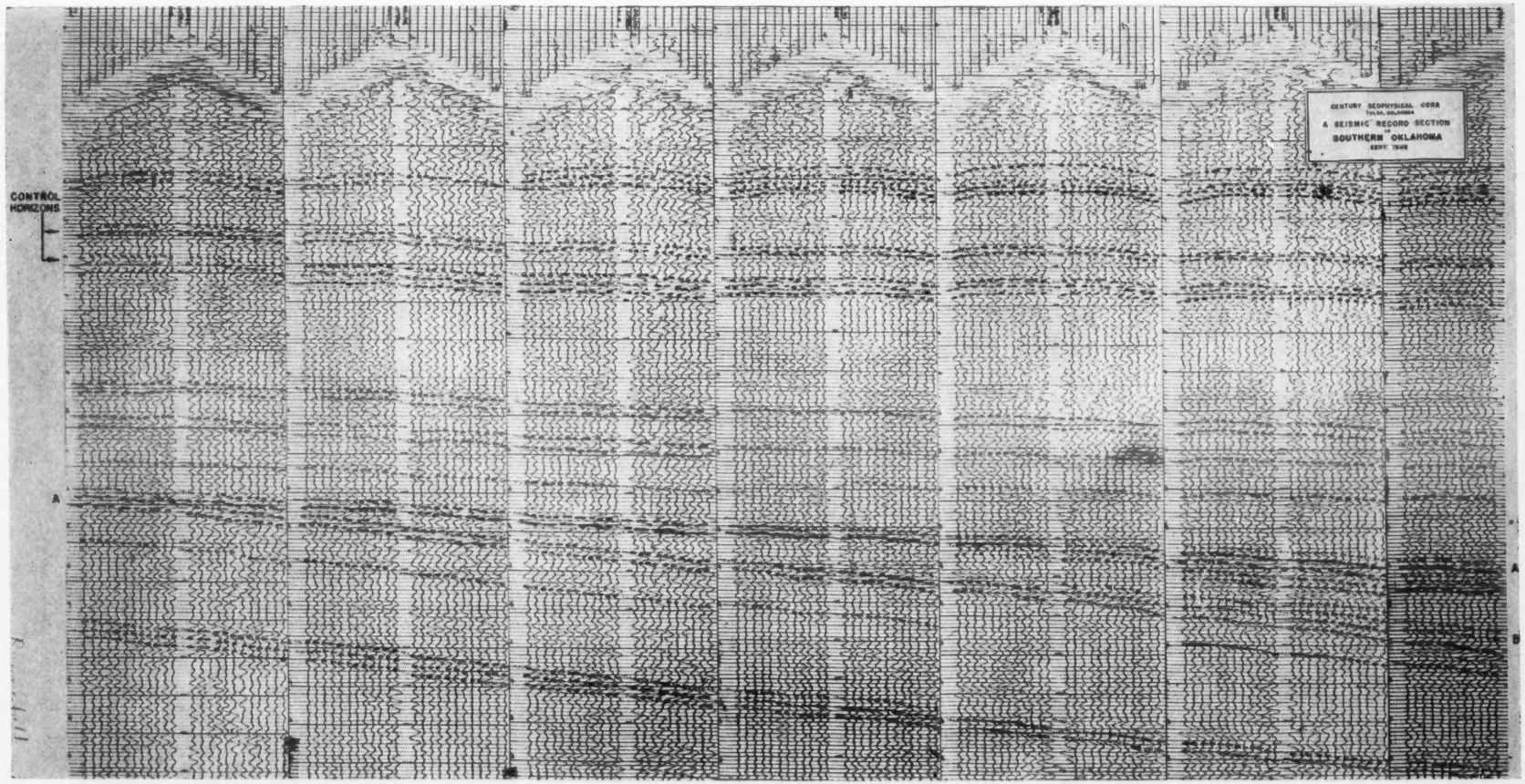


FIG. 4. Array of records shot in southern Oklahoma along a profile, illustrating convergence of two reflections (A and B) and resulting loss of identity of the deeper reflection.

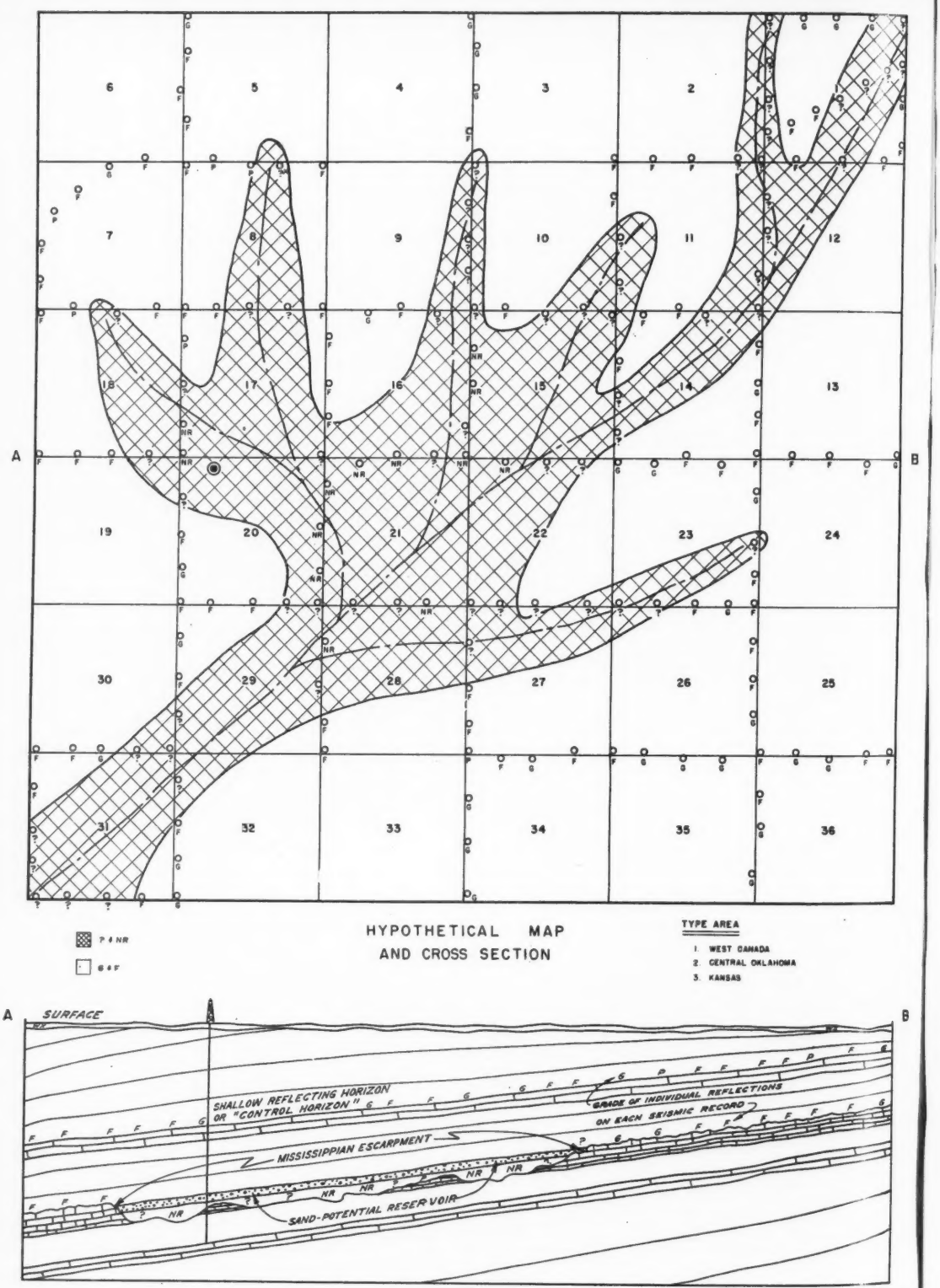


FIG. 5. Dendritic pattern in buried Mississippian topography as revealed by idealized reflection quality map.

edge of the Mississippian escarpment but also in establishing the presence of porous sands which replaced the eroded Mississippian section.

A similar problem exists in some areas of Oklahoma where Hunton topography influences subsurface studies and may lead to pseudo-structures on seismic maps.

Figure 6 illustrates a deep-seated faulted structure which is masked by an unconformity. An area of deep questionable reflections would be expected to coincide with the faulted anticlinal axis.

After considerable investigation and experience, it becomes apparent to the seismic interpreter that the particular zone in which he is normally most interested is quite often the zone of poorest seismic reflections and the zone most difficult to interpret. The first inclination is to write off this effect as "pure cussedness" and perversity of the seismic method. As an interpreter continues to encounter this problem, he reaches the conclusion that there may be valid reasons for his dilemma. It is known that oil accumulates in structural areas which deviate from the normal. It is further known that a simple plane acts as the best reflector and that the poorest reflections would be received from zones of maximum flexure. If faulting were to occur in competent beds, the areas in which the faulting most likely would take place would be in the zones of maximum curvature where the beds are subjected to the greatest stress. Therefore, trends of structural axes and/or faulting might be outlined by seismic quality maps. Figure 7 shows the loss of a deep reflection that was encountered on the down-thrown side of a fault. A deep reflection was evident on the down-thrown side of the fault in some areas, but the change in interval made any correlation across the fault quite questionable.

## APPLICATIONS

More marginal geological problems which might lend themselves to such analysis would be studies of fluid content, porosity of reflecting horizons, facies changes, and many others. *However improbable,* solutions to such problems should be attempted, for the resolving power of the seismic method is being constantly improved. Also, circumstances might combine in local areas to allow such evaluations. These suggested efforts are subject to personal judgment and error to a much greater extent than in any other presentation of seismic data.

The preparation of quality maps in the average area is a very difficult undertaking. If the reflection is persistent and the quality change is random, the construction of such a map may be a waste of time. On the other hand, it has been found after considerable study that the inconsistency itself of individual reflection quality in some areas may finally crystallize into a recognizable pattern. The delineation of such data is not necessarily structural, and must be of a reconnaissance nature. At times, the violation of one or several points may be advisable. Care must be exercised that the patterns, under these circumstances, are not being forced to substantiate some preconceived idea of the interpreter.

The use and value of these maps are, to a very marked degree, dependent

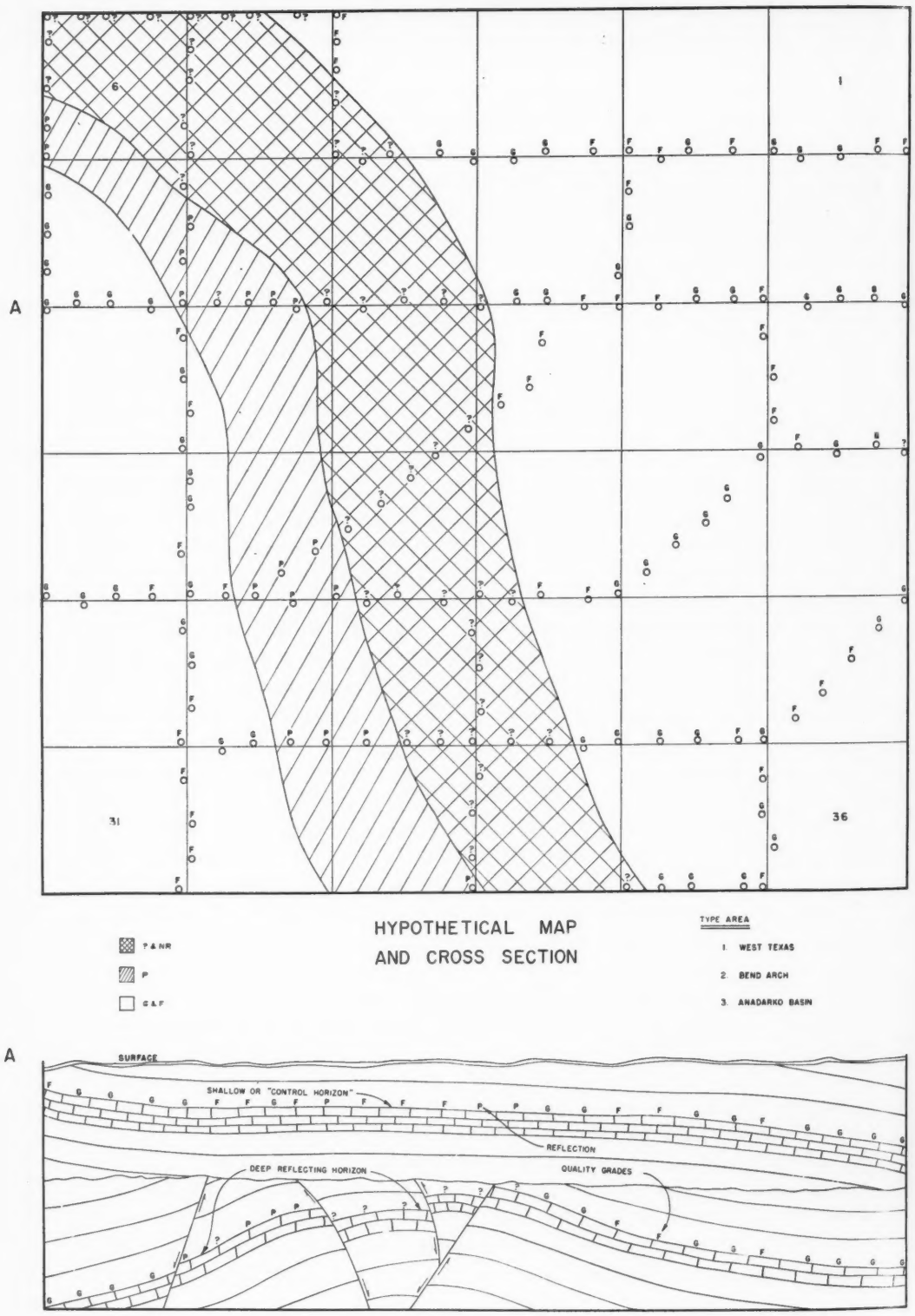


FIG. 6. Effect of deep-seated fault below an unconformity upon reflection quality as illustrated by a hypothetical quality map.

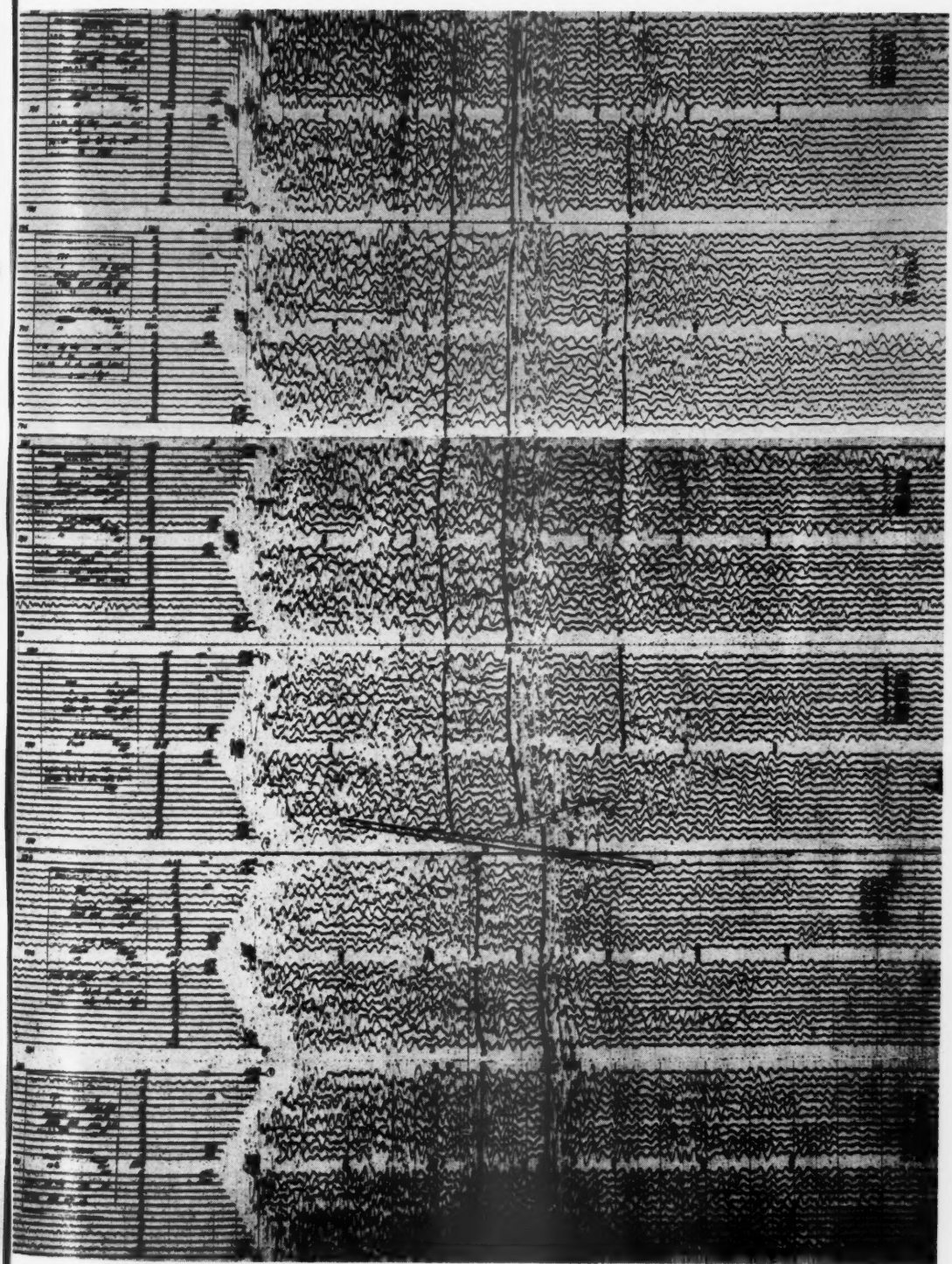

FIG. 7. Array of records illustrating loss of a deep reflection upon crossing a fault to the down-thrown side.

upon the imagination, ability, and experience not only of the interpreter but also of those in exploration management who must coordinate the general geological and geophysical data with all other knowledge of the area investigated. It cannot be overlooked that such studies impose a time-consuming, additional burden upon already overtaxed exploration personnel.

This approach may add a fourth dimension to normal seismic maps, and possibly may serve to illustrate that imagination, when controlled, is an exploration tool by which the geologist and the geophysicist can advance the effort to find oil. Further, *every* seismic record may become important from the viewpoint of evaluating oil possibilities and not merely those records "on structure."

It has been estimated that the exploration industry spends only 10 percent, or less, of total seismic costs on the analysis and interpretation of seismic data. The revision and reanalysis of work now existing in many exploration department files would, undoubtedly, bring to light many undiscovered oil fields. Such reanalysis might well prove to be the cheapest and most effective exploration work possible.

These facts spotlight the urgent need for additional interpretive talent and efforts. Until this need is fulfilled, the oil-finding effort of the industry will suffer, and potential deposits will continue to be overlooked.

GEOPHYSICS, VOL. XIX, NO. 4 (OCTOBER, 1954), PP. 695–715, 14 FIGS.

# SURFACE AND NEAR-SURFACE WAVES IN THE DELAWARE BASIN*

MILTON B. DOBRIN,† PHILIP L. LAWRENCE,† AND RAYMOND L. SENGBUSH†

## ABSTRACT

Seismic propagation studies made in the Delaware Basin of West Texas by the Field Research Laboratories of the Magnolia Petroleum Company have disclosed several unusual kinds of traveling waves. The near-surface zone in this area is characterized by alternating high- and low-velocity layers, with a thin high-velocity cap. Physical characteristics of the recorded waves have been correlated with this layering.

Five types of waves have been identified: 1) Waves refracted along the tops of high-speed near-surface markers which have been multiply reflected, at the critical angle, between the marker beds and interfaces nearer the surface. 2) Shear waves refracted at shear velocity along a competent bed several hundred feet deep. 3) Compressional waves propagated by normal-mode transmission in the wave guide formed by a low-speed layer situated between two high-speed layers. 4) A single-cycle, apparently non-dispersive Rayleigh wave propagated in a thin limestone surface layer and in an underlying low-speed layer of sand and gravel. 5) An inversely dispersive Rayleigh wave train in which the group velocity appears to decrease with increasing wave length; this type of dispersion, just the opposite of the kind ordinarily recorded, is attributed to the fact that the low-speed surface layer is unusually thick compared with the wave length corresponding to the cut-off frequency of the instrumental system.

## INTRODUCTION

In 1951, an experimental seismic crew of the Magnolia Petroleum Company Field Research Laboratories investigated several areas in the Delaware Basin where difficulties had been encountered in obtaining reflections. As one part of this program, a study was made of the waves traveling on or near the surface that might mask energy reflected from beds at greater depths. The near-surface lithology over much of this area is unusual and it appeared likely that the unique layering could give rise to traveling waves that might account for some of the difficulties experienced by reflection crews operating there. The Magnolia research group observed several unusual types of traveling waves with characteristics that could be associated with the elastic properties of the near-surface layers. It is not likely that these waves mask reflections in any substantial way, particularly when multiple geophone and shot combinations are used. They do cast interesting light, however, on the elastic wave transmission to be expected where there is complex surface layering of the type that occurs over much of the Delaware Basin.

At the location chosen for the experiments to be described here, the near-surface zone is characterized by alternating high- and low-velocity layers with a thin high-velocity cap. Stratification of this type might be expected to result in wave-guide propagation of seismic energy. Moreover, surface waves in such a lithology might be expected to show unusual characteristics. Among traveling waves identified on the field records are a group showing evidence of wave-

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guide origin and a number of predictable surface wave types that have seldom been observed elsewhere.

## ELASTIC PROPERTIES OF NEAR-SURFACE LAYERS

The location for our experiments was in Reeves County, Texas, about 20 miles southeast of Pecos. The profile along which most of our records were shot was the north line of Block 51, Township 8.

The lithologic and elastic characteristics of the near-surface formations were determined from a number of test boreholes along this profile. The depths of these holes ranged from 450 to 800 feet. Geological information was obtained from samples collected when the deep boreholes were drilled and from electric logs. Elastic wave velocities (compressional and shear) were determined from elastic logs of the type described by White and Sengbush (1953) up to depths of about 400 feet, and compressional speeds were determined by refraction methods for greater depths. Figure 1 shows a composite log of lithology, vertical compressional velocity, and vertical shear velocity along the profile where the seismic recording was carried on. The high-speed cherty surface layer, 30 feet thick, and the anomalously low-speed gravel and clay layer between this and the water table are not typical of the near-surface lithology usually encountered in areas where reflection shooting is conducted. Shear velocity could not be measured by water-pulse methods below about 200 feet but it is possible to approximate the speeds in deeper strata (which are all consolidated) by assuming the theoretical relation between shear and compressional speed ($1:\sqrt{3}$) in an ideal solid. The discontinuity in compressional speed at 85 ft is attributable to the water table. This accounts for the absence of a discontinuity in shear velocity at the same depth.

## FIELD PROCEDURE

Seismic equipment used for these studies differed from the conventional prospecting type in that all frequencies between 5 and 200 cps were passed with a flat over-all amplitude characteristic. Another departure from prospecting procedures was the integration of the output signals, proportional to the velocity of ground motion, so that the final recording represented ground displacement. Horizontal geophones were employed along with vertical geophones to determine particle trajectories of various earth vibrations.

Traveling waves were studied on record arrays made from detector spreads along a 5,000 ft profile. The individual spreads (corresponding to the 12-trace records) were 450 ft long with 50 ft between vertical detectors. At the first detector position of each spread, two horizontal geophones, one oriented along the profile and the other perpendicular to it, were placed next to the vertical geophone. Thus the first three traces of each record show the three components of ground motion at the beginning of the corresponding spread.

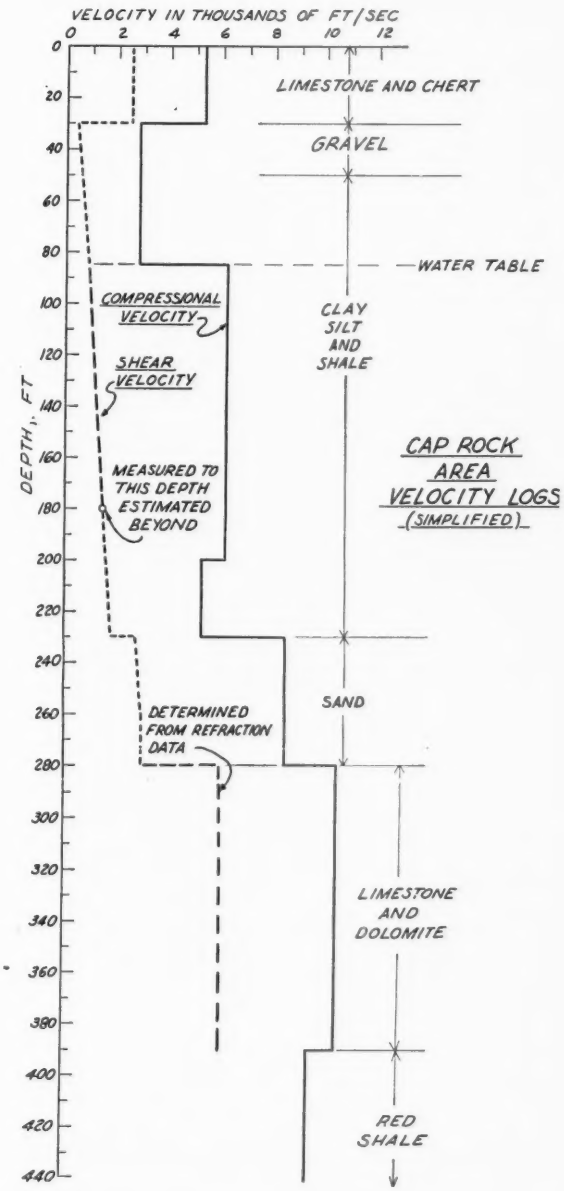
VELOCITY IN THOUSANDS OF FT/SEC
0 2 4 6 8 10 12
DEPTH, FT
0 20 40 60 80 100 120 140 160 180 200 220 240 260 280 300 320 340 360 380 400 420 440
LIMESTONE AND CHERT
GRAVEL
WATER TABLE
COMPRESSIONAL VELOCITY
SHEAR VELOCITY
CLAY SILT AND SHALE
MEASURED TO THIS DEPTH ESTIMATED BEYOND
CAP ROCK AREA VELOCITY LOGS (SIMPLIFIED)
SAND
DETERMINED FROM REFRACTION DATA
LIMESTONE AND DOLOMITE
RED SHALE

FIG. 1. Logs of lithology and of compressional and shear velocities to depth of 450 ft in Cap Rock area.

## RECORD ARRAYS

An array of eleven records covering the shot-detector distance range from 60 to 5,110 ft was shot with 5-lb charges at a depth of 50 ft in the shot hole. Another

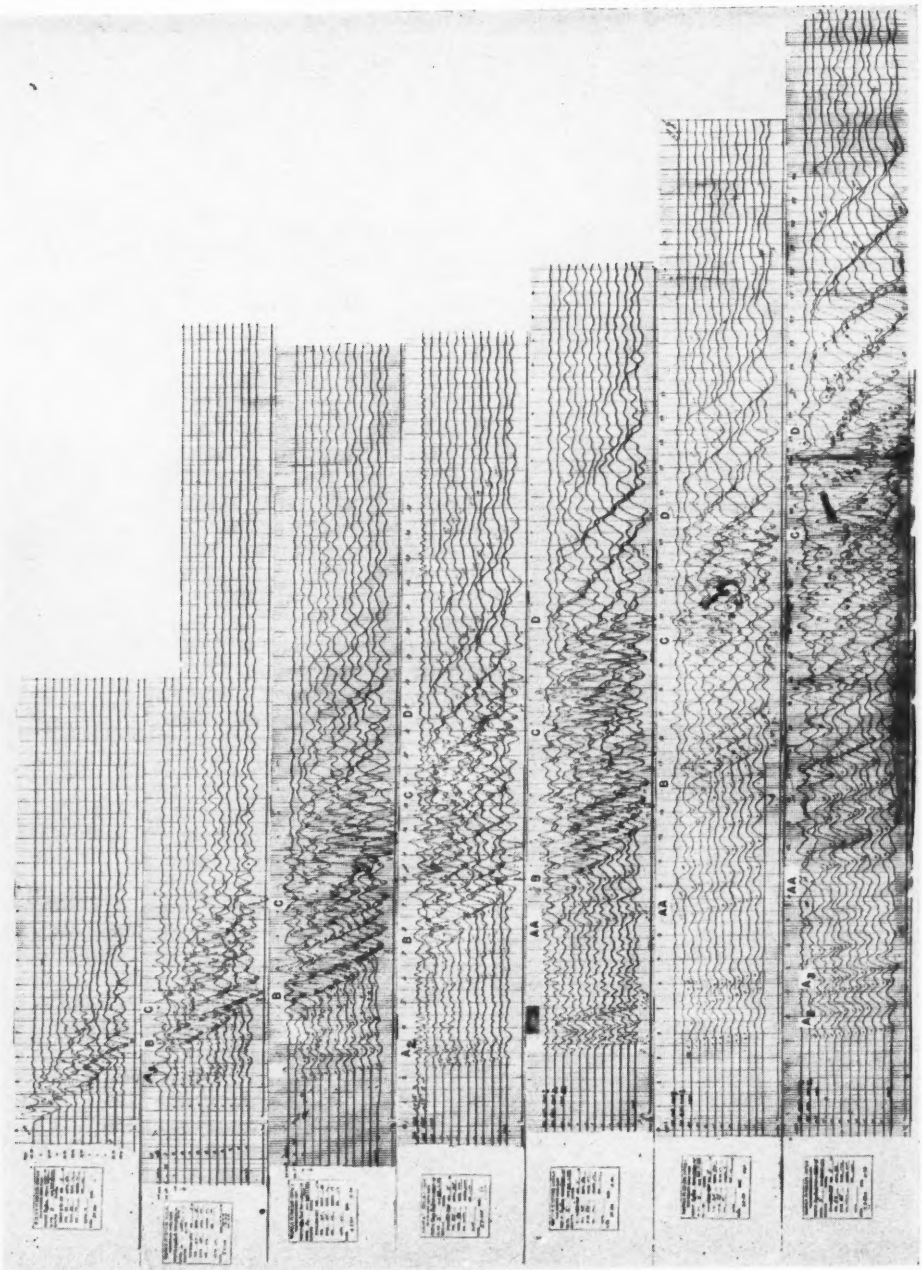

FIG. 2. Record array showing wave propagation from shots 50-ft deep over distance range from 60 to 3,310 ft from shot point. The first two traces of each record show horizontal radial and horizontal transverse motion. The remaining traces show vertical motion at 50-ft intervals. The last trace of each record should be coincident with the third trace of the next record.

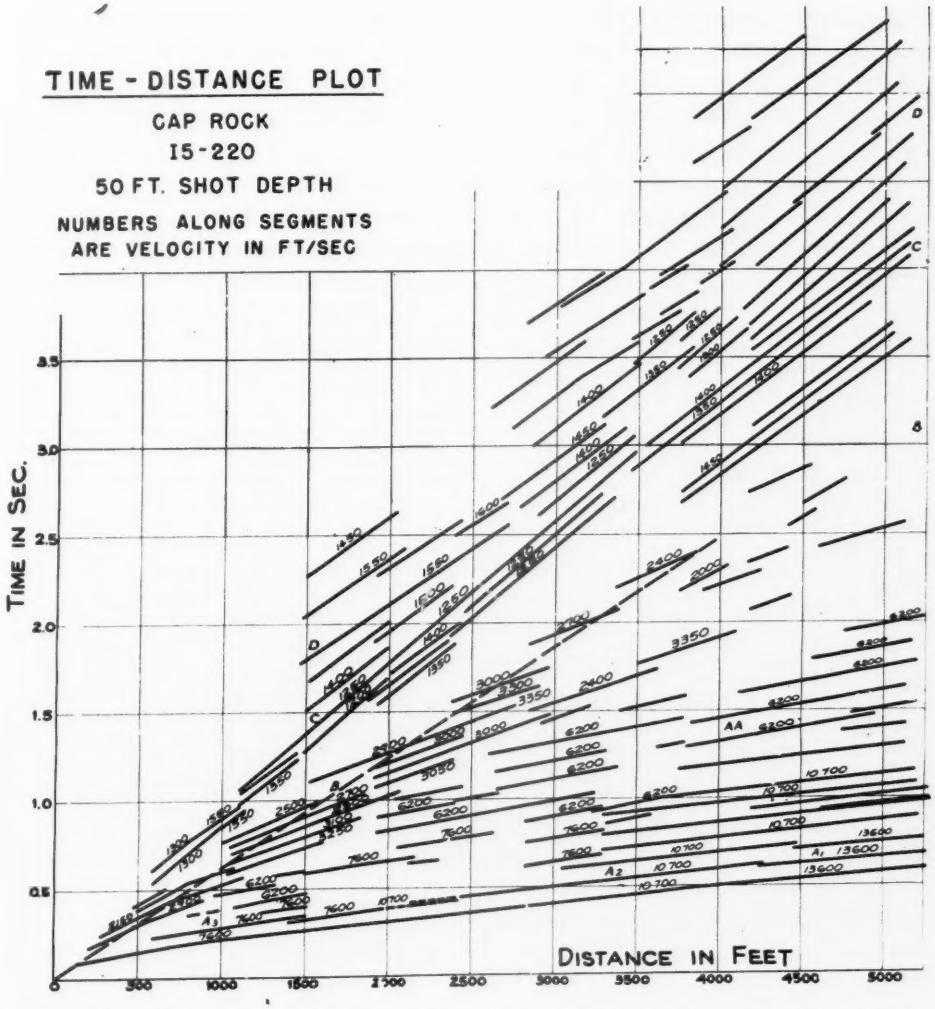


FIG. 3. Time-distance plot showing all traveling wave troughs recorded from 50-ft shots out to a distance of approximately one mile.

array was shot, with detector positions beyond 1,500 ft from the shotpoint, with charges fired at 150-ft depth.

Figure 2 shows the records obtained with spreads up to 3,100 ft from the 50-ft shot hole. A number of events are observed to travel across the records. These are separated into four groups, labeled A to D, having discrete characteristics. The first two, A (including AA) and B, are believed to be body waves traveling in near-surface formations. The others, C and D, are interpreted as surface waves.

Figure 3 is a time-distance plot of all traveling events (wave troughs only)

observed on the records of Figure 2 and also on the records (not reproduced) covering the range from 3,110 to 5,110 ft. Segments corresponding to the various groups of waves indicated on the record array are designated by the corresponding letters on the plot. It is evident that many of the traveling wave phases persist for thousands of feet along the profile.

The various groups of events have been tentatively identified as follows. In group A are waves refracted by near-surface high-speed layers and multiply reflected from interfaces above. In group AA are waves postulated to be refracted shear waves, although other interpretations are possible. The group B

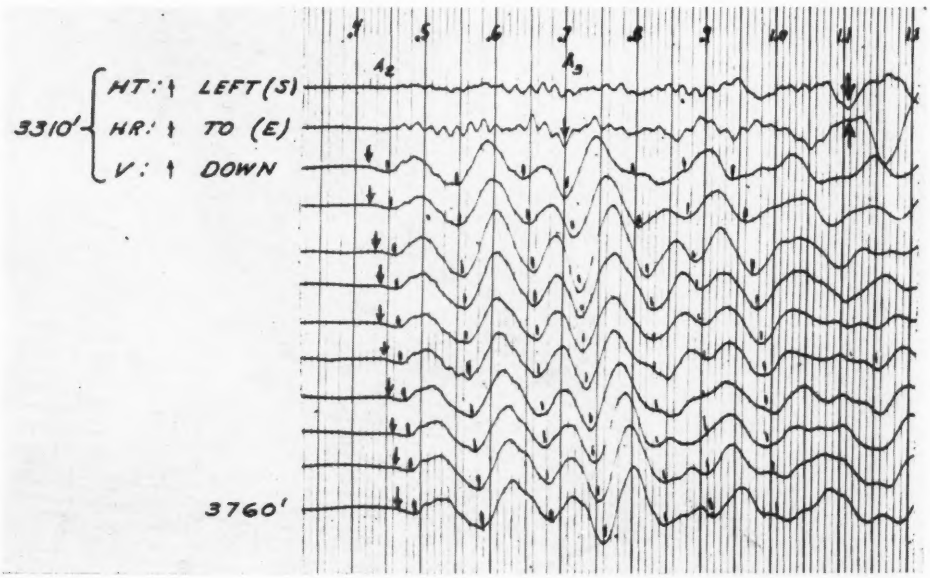


FIG. 4. Portion of record, made with geophones at 50-ft intervals from 3,310 to 3,760 ft, showing multiply-reflected refraction waves. First two traces show components of horizontal ground motion at 3,310 ft. The remainder show vertical motion. Shot depth is 50 ft.

events are believed to result from normal-mode wave guide propagation in the low-speed zone between the high-speed cap-rock surface layer and the water table. Group C events appear to be non-dispersive Rayleigh waves associated with the cap-rock layer on the surface. The last group, D, is the inversely dispersive Rayleigh wave controlled by the thick layer above the high-speed interface at a depth of 280 feet.

## MULTIPLY REFLECTED REFRACTIONS

The characteristics of the first group of waves are rather clearly shown on the reproduced portion (Fig. 4) of the record made from a geophone spread extending from 3,310 to 3,760 ft. The shot was 50 ft deep. The top trace represents

the horizontal motion transverse to the profile, the second trace the horizontal motion along the profile, and the remaining traces the vertical motion at 50-ft intervals. The vertical geophone for the third trace is at the same position (3,310 ft from the shot) as the two horizontal geophones.

The first three cycles of the wave train have a constant period of .09 sec, a step-out velocity of 10,700 ft/sec (equal to that of the first break), and ground motion that is essentially vertical. The fourth cycle has a larger amplitude of vertical motion but the particle trajectory is now inclined about 30° with respect to the vertical while remaining in the vertical plane through the profile. The period increases with increasing distance from the shot. Later cycles are not well defined; periods tend to be shorter, about .06 sec, and the velocity is roughly 7,500 ft/sec. Particle trajectories are essentially linear and inclined to the vertical. Waves similar to these are observed with 13,600 ft/sec velocity at greater spread distances.

The identification of these waves as refractions from near-surface high-speed markers is based largely on the coincidence between their step-out times and that of the first arrivals from the respective beds. The predominance of vertical ground motion on the surface supports this interpretation. The succession of cycles with these step-out times in the wave train is explained by multiple downward reflection of the refracted waves (at the critical refraction angle) from some interface above the refractor. Since the higher-frequency components in the pulse are dissipated, the repeated arrivals appear as a low-frequency train. Each cycle corresponds to waves reflected back to the refractor a different number of times.

If we assume this explanation, the periodicity of the waves can be predicted from the delay time associated with the vertical travel path between the refractor and some reflecting interface above. The time lag corresponding to the round trip is equal to the interval between the first arrival and the arrival of the doubly-refracted wave. The same interval is observed between the latter wave and the one that has been reflected downward twice.

In the case of a refractor overlain by a single low-speed layer, repeated arrivals of the same phase should be separated by an interval equal to twice the intercept time for the refracted ray, assuming a phase reversal to occur upon reflection at the free surface. The periods of all waves observed here are, however, much too short to be explained by refraction-path travel times between the earth's surface and the refractors. The discrepancy can be removed if we assume that the downward reflections are not from the free surface but from the base of shallower high-velocity layers, representing the paths along which there is least loss by attenuation. Time delays for secondary arrivals were computed, assuming that the multiple path with least attenuation loss was that between the refractor and the base of the first high-velocity layer above the refractor. On this basis, repeated refraction arrivals would be separated by .08 sec for $A_3$, .11 sec for $A_2$, and .10 sec for $A_1$. These values compare favorably with measured periods of .06

to .07 sec for $A_3$, .10 sec for $A_2$, and .09 sec for $A_1$ wave trains. Figure 5 illustrates these multiple paths.

Multiply refracted arrivals similar to those observed by us have been reported by Leet (1950, p. 108–109). In the case he considers, however, the multiple reflection appears to take place at the free surface. Johnson (1943) has proposed the same mechanism to explain some spurious waves reported in a paper by Deacon (1943).

## EVENTS ASSUMED TO BE REFRACTED SHEAR WAVES

Figure 6 shows waves of the second group (AA of Figures 2 and 3) on a record made with a spread covering the distance range 2,860 to 3,310 ft from a 50-ft

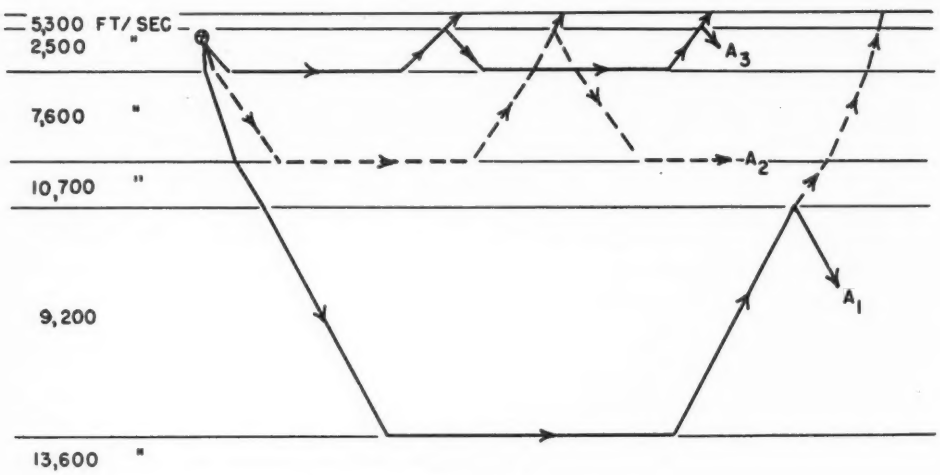


FIG. 5. Possible wave paths for multiply-reflected refraction waves observed in Cap Rock area.

shot. The components of horizontal motion at the 2,860-ft position are shown on the first two traces. These waves have a step-out velocity of 6,200 ft/sec and show somewhat greater displacement amplitude in the vertical direction than in the horizontal plane. Although the components do not maintain a uniform phase relationship during passage of this wave train, the initial cycle shows retrograde, roughly elliptical motion in a vertical plane making an angle of about 45° with the vertical plane of the profile.

Onsets of this event are somewhat earlier on the horizontal than on the vertical geophones. Projection of the horizontal onsets to the zero-distance axis on the time-distance plot gives an intercept time that would be expected if the event were a shear wave refracted from the top of the high-speed bed 280 ft deep (which has a compressional speed of 10,700 ft/sec). A shear velocity of 6,200 ft/sec would be quite reasonable for this bed, being about 0.6 times as large as

the compressional speed. In computing the predicted delay time for a shear wave refracted from this marker, the average shear speed logged to 200 ft was assumed to hold down to 280 ft.

It thus appears that the waves in group AA may be refracted shear waves. The wave-forms are too poor, however, for positive identification.

## NORMAL-MODE PROPAGATION IN LOW-SPEED LAYER

The waves designated as group B in Figures 2 and 3 have some unusual characteristics which suggest that they propagate in the wave guide that results when a low-speed layer (that below the surface cap-rock) is sandwiched between two formations of higher seismic velocity. The waves are well developed when

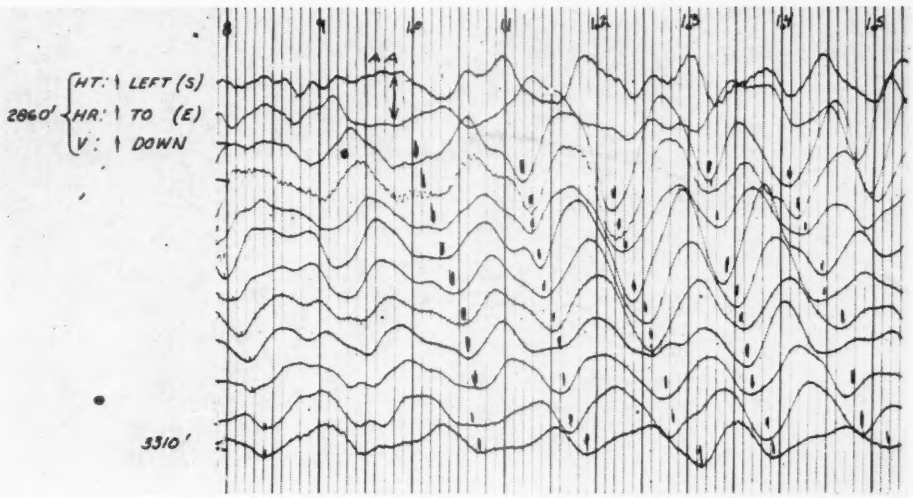


FIG. 6. Portion of record showing waves assumed to be refracted shear waves. Traces correspond to geophone spread covering range from 2,860 to 3,310 ft, with phones 50 ft apart. First two traces show components of horizontal ground motion at 2,860 ft. The remainder show vertical motion. Shot depth is 50 ft.

the shot is fired above the base of the low-speed zone but they disappear when the source is below the water table, constituting the zone's lower boundary.

Figure 7 illustrates the propagation of these waves over the distance interval between 1,510 and 1,960 ft from the shot, which is 50-ft deep. The propagation velocity for any particular cycle is about 3,000 ft/sec. The band of maximum energy appears to shift continuously from earlier to later cycles as the shot-detector distance increases. This effect, observable to some extent on Figure 7, is conspicuous over the entire distance range (about 2,800 ft) within which this wave could be followed (see Figure 2). The dotted line drawn through segments of the B group on the time-distance plot of Figure 3 represents the position of maximum amplitude. The inverse slope of this line, 1,600 ft/sec, is the group

velocity with which the maximum energy was propagated. This group velocity is thus observed to be about half the phase velocity as determined from step-out times of individual phases in the wave train. The period of the maximum cycle remains constant at 0.056 sec. During the passage of the maximum, the particle trajectory is linear. The line of motion makes an angle of about 30° with the vertical and its horizontal projection makes an angle of about 45° with the profile. For other cycles of this wave train, the particle trajectory cannot be described in simple terms.

In further investigation of this wave, a vertical geophone adapted for borehole

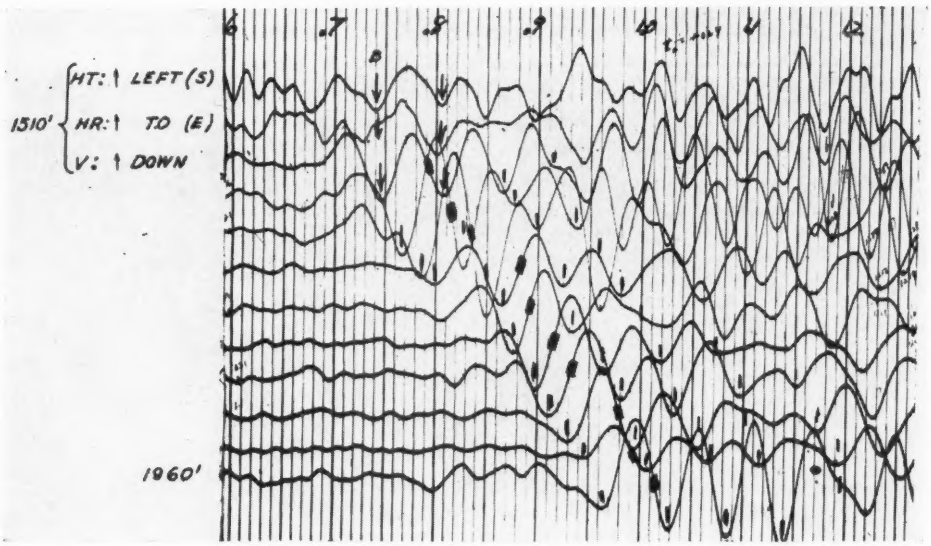


FIG. 7. Portion of record showing waves identified as propagating in low speed layer acting as wave guide. Traces correspond to geophone spread covering interval between 1,510 and 1,960 ft from shot, with a phone spacing of 50 ft. First two traces show components of horizontal ground motion at 1,510 ft. The remainder show vertical motion. Shot depth is 50 ft.

measurements recorded the wave at various depths up to 85 ft. In Figure 8, the full line shows the amplitude of this wave as a function of depth. The changes with depth in the vertical amplitude components of the first break and of one cycle of the Rayleigh waves are also shown for comparison. The horizontal bars indicate the range of amplitudes recorded from several cycles of the wave train, the curved line approximating the trend. Note the reversal in phase at a depth of 40 ft. The phases would be expected to shift 180°, for the wave lengths represented, at depths between 38 and 43 ft. This amplitude pattern is a typical one for standing wave propagation such as one would obtain from a wave guide. Moreover, the amplitude variation and phase reversal would rule out refraction from any depth greater than 40 ft. For a three-liquid layer case, with a minimum velocity layer between two higher velocity layers, Pekeris (1948) has shown that

there will be a pressure maximum approximately in the middle of the low-speed member. This calls for a vertical-particle-velocity null at this position as well as a change of phase in the vertical component. Such an analogy could explain the amplitude minimum and phase change observed here. The linear particle trajectory which we observed would not, however, be expected from normal-mode considerations. The waves do not show the variation of period with time that is

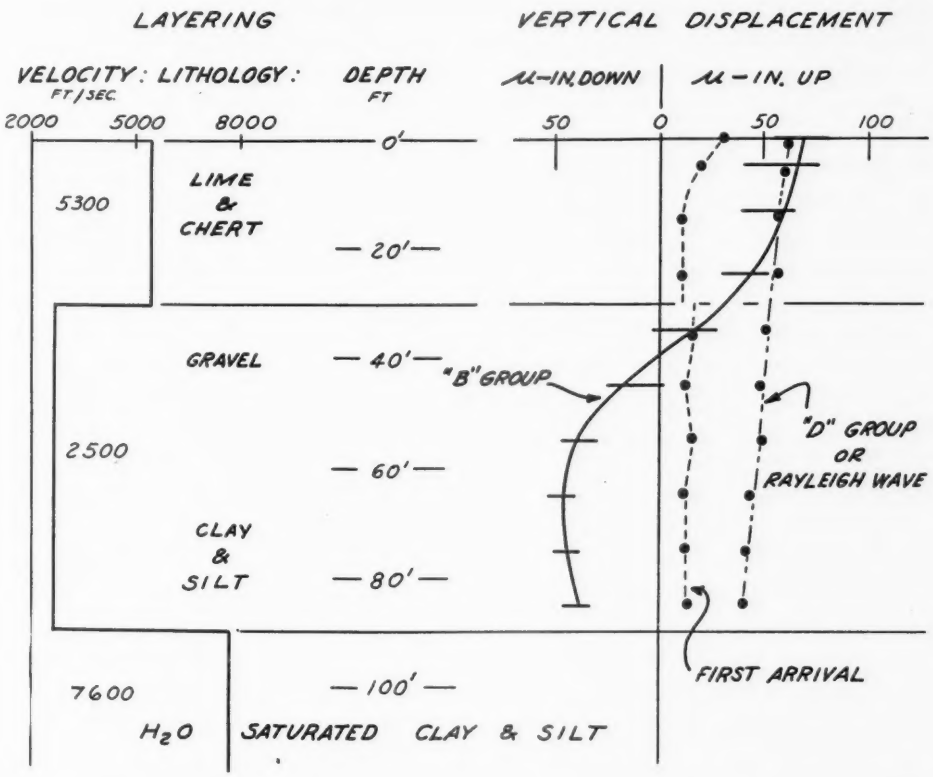


FIG. 8. Amplitude of waves in group B as function of recording depth to 85 ft. Note phase reversal at about 40 ft. Compare this curve (full line) with curves of first arrival amplitude and Rayleigh wave amplitude (both indicated by dashed lines) as functions of depth.

ordinarily observed in dispersive wave-guide propagation; only a very narrow band of frequencies is propagated. It is possible, however, that the observed frequency range corresponds to an Airy-type group velocity minimum, the energy at other frequencies being too weak to give recordable signals.

As an alternative explanation, the compressional components of the wave repeatedly reflected within the low-velocity gravel layer may sweep the interface at the base of the cap material at the shear velocity within the cap and thus sustain a horizontally traveling shear wave in the uppermost high-speed layer.

This possibility is suggested by the coincidence between the measured shear velocity in the cap (Fig. 1) and the group velocity of the observed wave, as well as by the particle trajectory.

Waves somewhat similar to these have been reported by B. F. Howell (1949), who conducted some experiments on near-surface wave propagation of waves from shot-hole explosions in Southern California. Howell's waves, which he identified with the "coupled waves" of Leet (1939), have a velocity and particle trajectory similar to those we have observed; they also show a shift of maximum energy from earlier to later cycles at increasing distances from the source. Although there is no indication of a low-speed layer near the surface where Howell conducted his experiments, it would not have been possible to observe such a layer by the refraction methods he employed to study the near-surface velocity distribution. If such a layer should exist there, it would have to be considerably thicker than the 55-ft low-speed zone at our West Texas location since his "coupled waves" have about three times the period of our "B waves" and persist over a greater distance range.

### RAYLEIGH WAVES IN CAP ROCK AND LOW-SPEED SUBSTRATUM

The waves of group C (Figure 2) were observed only from the shots at a depth of 50 ft. They could not be found on records shot at 115 ft or deeper. Figure 9 shows the propagation of waves belonging to this group at two distance ranges. The top record covers the interval from 2,410 to 2,860 ft while the bottom record, recorded with lower gain, is for the 1,060 to 1,510-ft interval. The horizontal motion transverse to the profile is weak and the vertical plane of motion is within 25° of the plane of the profile. The phase relation between the horizontal and vertical motion at the detector position nearest the shot indicates elliptical retrograde motion, the vertical axis of the ellipse being three times the horizontal. Although this amplitude ratio is about twice that called for by the theory Rayleigh (1885) developed for a semi-infinite homogeneous elastic solid, it appears reasonable to identify this as a Rayleigh wave. The step-out velocity of the wave (see Fig. 3) averages about 1,300 ft/sec.

Most of the wave's energy appears to be concentrated in a single cycle. The time-distance segments corresponding to the maximum energy troughs on successive records are continuous and the resulting line, labeled C, on the time-distance plot of Figure 3, projects back into the origin with an inverse slope of about 1,300 ft/sec. Since periods of successive cycles are the same, and since the group and phase velocities are equal, the wave does not appear to be dispersive. The period is 0.085 sec, so that the wave length is about 110 ft.

At a depth of 50 ft, the impulse exciting this wave is very close to the relatively thin high-speed surface layer underlain by a material with a lower seismic shear velocity. Since it is shear rather than compressional speed that governs Rayleigh wave characteristics, the substratum effectively extends from the base of the hard-surface limestone zone at 35 ft to the next shear discontinuity at 280 ft.

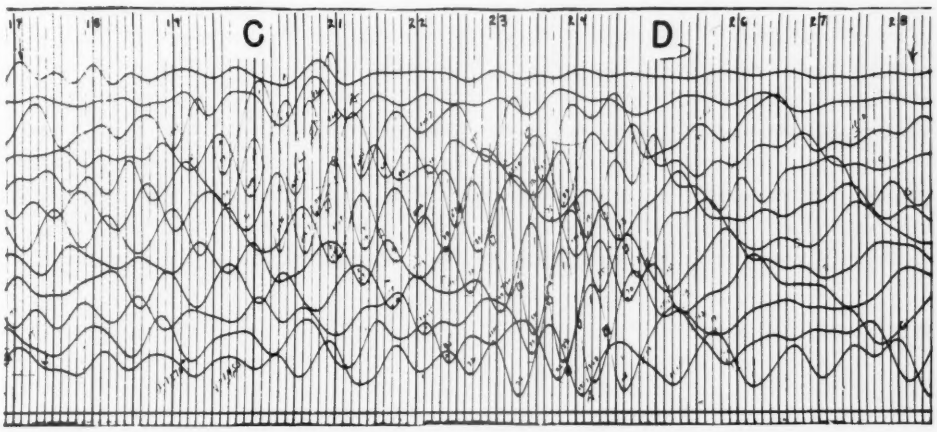


FIG. 9. Propagation of Rayleigh waves showing no apparent dispersion as indicated by geophone spreads covering two distance ranges. Shot depth 50 ft. First two traces of each record show components of horizontal motion at 4,660 ft. The remaining traces show vertical motion from 5,660 to 5,110 ft.

This means that for short wave lengths we effectively have a two-layer situation with the upper zone having the higher speed.

Rayleigh wave propagation in a system comprising a high-speed surface layer overlying a lower-speed semi-infinite substratum has never been given as complete a theoretical treatment as in the case of a low-speed surface layer over a higher-speed substratum. Because of the complexity of the calculations involved, no complete dispersive curves are available in the literature for the case of the high-speed surface layer. However, Fu (1946) has discussed this situation briefly and has shown that there are limits to the range of wave lengths within which

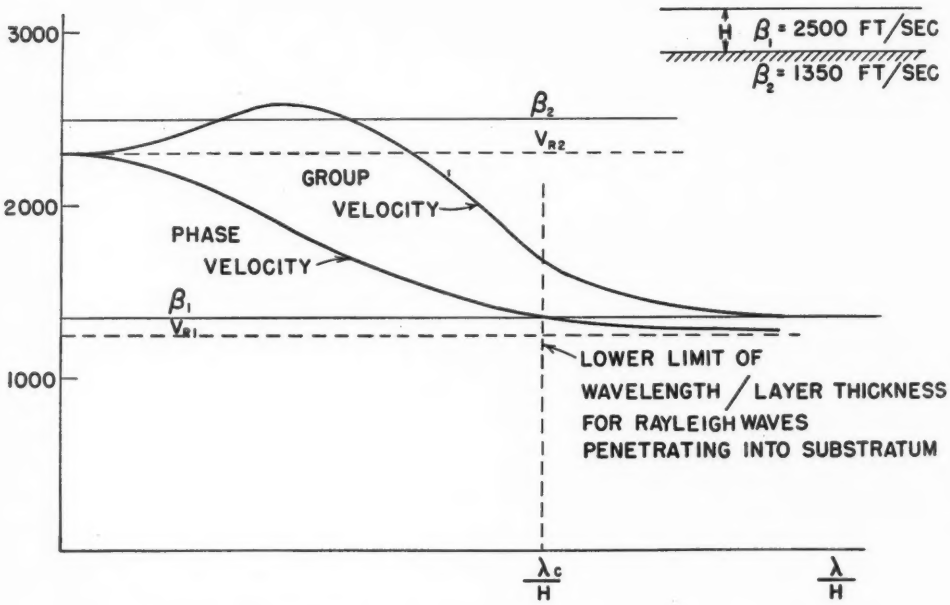


FIG. 10. Schematic dispersion curves for case of high-velocity surface layer overlying lower-velocity semi-infinite substratum. The $\beta$'s are shear velocities in the respective media and the $V_R$'s are Rayleigh-wave velocities.

such Rayleigh waves can exist. Specifically, they cannot be transmitted at any wave length shorter than that for which the phase velocity equals the shear velocity in the low-speed substratum.

Figure 10 shows schematic group and phase velocity curves for the case of a surface layer with a shear speed of 2,500 ft/sec underlain by a very thick substratum having a shear speed of 1,350 ft/sec. These speeds correspond to the shear velocities actually measured in the two uppermost layers at our field location (see Fig. 1). From these curves, one would predict that Rayleigh waves fulfilling Fu's condition ($\lambda > \lambda_c$) would have to penetrate deeply into the substratum, so that $\lambda/H \gg 1$. Also, since the allowed region is one where the group

velocity curve has little slope, a very limited amount of dispersion and a short duration of the wave train would be expected. By the same reasoning, the group velocity should be only slightly greater than the phase velocity, if distinguishable at all.

The Rayleigh wave we have labeled C on our records appears to fit all of these predictions. The cut-off phase velocity of 1,350 ft/sec, which is indicated by Figure 10, is, at most distances, the maximum step-out velocity measured for this wave (see Fig. 3). The observed wave length/layer thickness ratio of 110/30 requires substantial penetration into the substratum, as would be expected from the dispersion curves. The short duration of the wave trains and the near-equivalence of the group and phase velocities also conform to what has been predicted.

Since excitation of Rayleigh waves falls off exponentially as the depth of the exciting source divided by wave length (Jeffreys, 1927) we should not expect a shot at, say, 150 ft to generate 110-ft Rayleigh waves nearly as effectively as a 50-ft shot. The relationship explains why waves of this type are not observed when the shot is 115 ft or more deep.

In addition to the Rayleigh waves penetrating deeply into the substratum, other Rayleigh waves could be propagated with such a short wave length that for all practical purposes they do not penetrate below the high-speed surface layer at all. The characteristics of these waves would be governed entirely by the elastic properties of the surface material and their propagation velocity would be approximately 0.92 times the shear speed in this medium.

In the case of the 30-ft high-speed surface layer encountered in our field measurements, it can be shown that waves of such a short wave length that they have no effective penetration into the substratum would have a period of only a few thousandths of a second. Waves of such high-frequency, if generated at all, would be scattered and attenuated so rapidly that they could never be observed in experiments of the type described in this paper.

## RAYLEIGH WAVES WITH REVERSE DISPERSION

At the end of each record made with shot-detector distances greater than 1,500 ft, Figure 2 shows a train of long-period waves that continue for an increasing number of cycles as the distance from the source increases. The waves in this group appear more regular when the shots are deeper. Figure 11 shows two views of a record made from a shot 150 ft deep with geophones covering the distance range from 4,660 to 5,110 ft. The high amplitude, non-dispersive wave that was so conspicuous on the records from the 50-ft shots has disappeared. The only traveling waves that appear after the early part of the record are in a sharply-defined dispersive sinusoidal train beginning at about 4.0 seconds. The particle motion of these waves is clearly elliptical and retrograde in the vertical plane of the profile (see Fig. 12). Although the ratio of vertical to horizontal amplitude is about 3:1 instead of the 1.47:1 called for by theory, it is still reason-

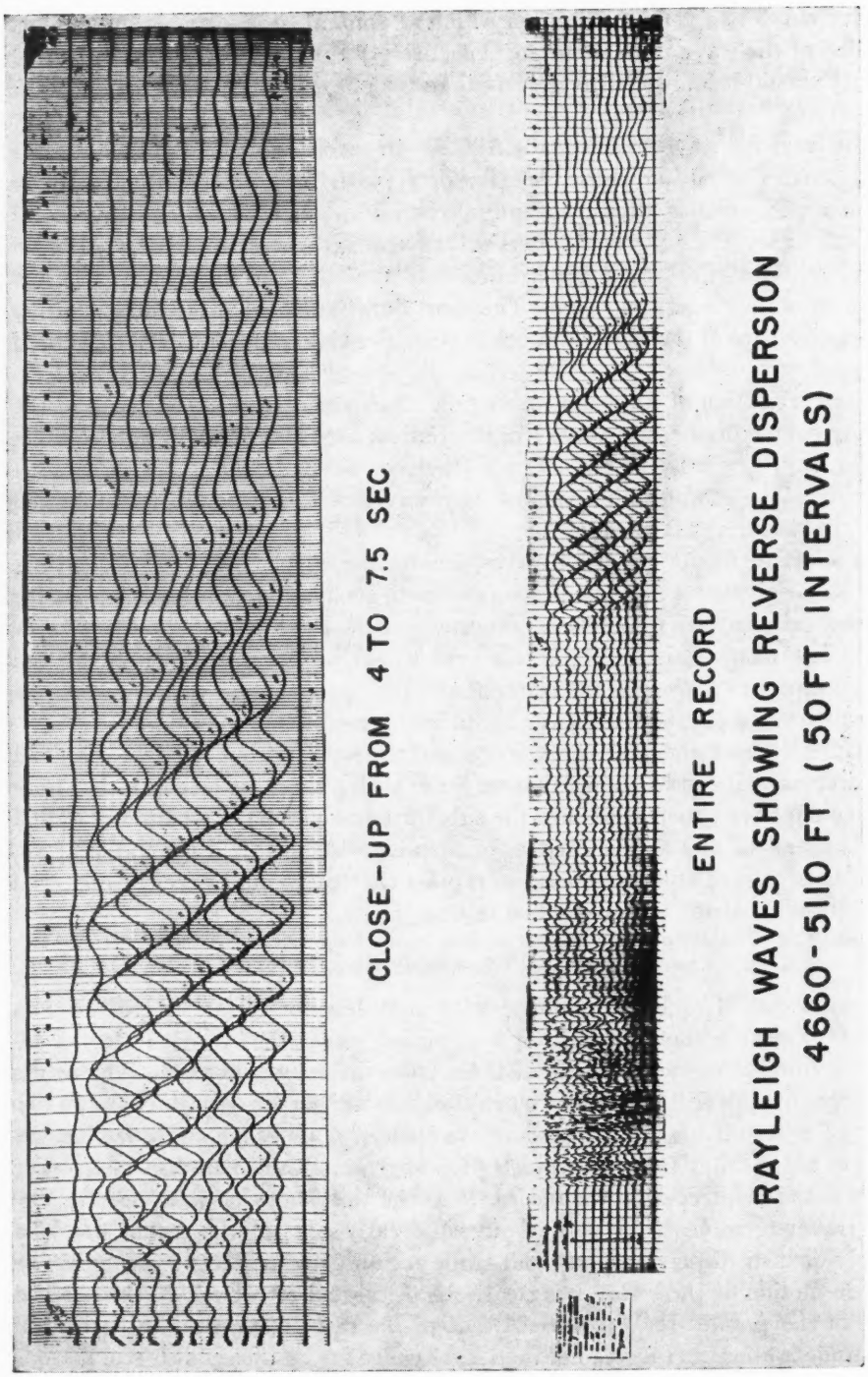


FIG. 11. Two views of record from shot at 150 ft made with geophone spread covering the range from 4,660 to 5,110 ft. Long sinusoidal train consists of inversely dispersive Rayleigh waves.

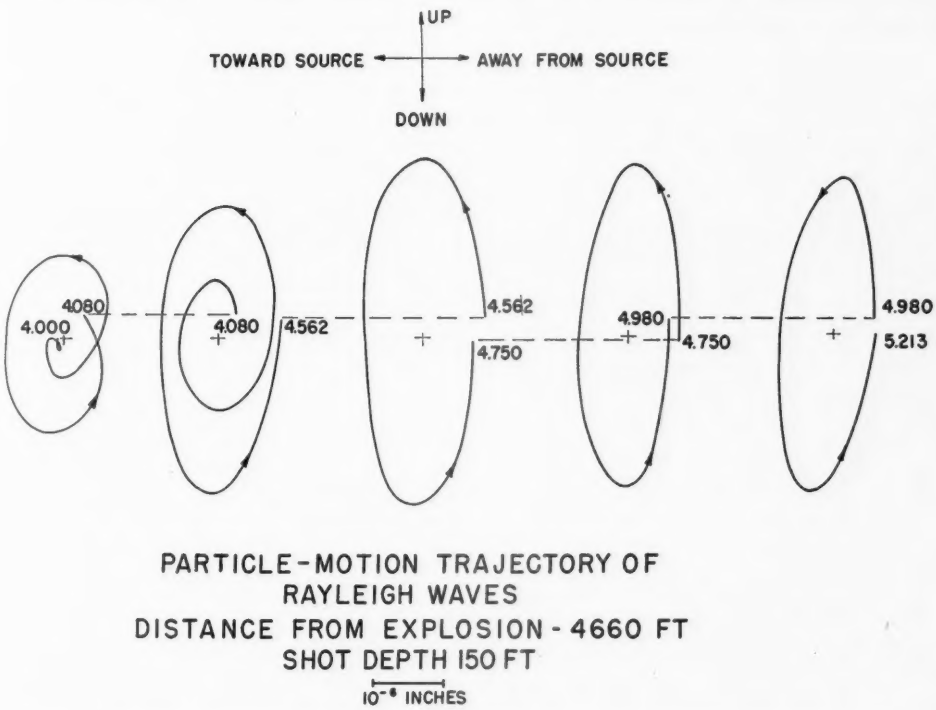


FIG. 12. Particle trajectories for five successive cycles of inversely dispersive Rayleigh waves.

able, in view of the near-surface inhomogeneity in lithology, to identify this event as a Rayleigh wave train.

The most unusual characteristic of these waves is the type of dispersion they show. In most previous observations of Rayleigh waves from small explosions (see, for example, Dobrin, Simon, and Lawrence, 1951) and in virtually all recordings, with conventional instruments, of Rayleigh waves from earthquakes, the group velocity increases with decreasing frequency and the observed wave trains start with the longest periods, successive cycles showing shorter periods as time increases on the record. The dispersion in the Rayleigh waves of Figure 10 is in the opposite sense, the periods becoming systematically longer with time. Thus the shorter wave lengths have the higher group velocities.

The phase velocity is observed, both from Fourier analysis and from measurement of step-out speeds of successive cycles on the records, to be higher than the group velocity and to increase with increasing wave length while the group velocity is decreasing. These relationships appear to rule out the possibility that the reverse dispersion can be attributed to the high-velocity surface layer, since the dispersion curves for this case (Fig. 10) require a phase velocity that is always lower than the group velocity and that decreases with increasing wave length. These same considerations eliminate the possibility that the wave results

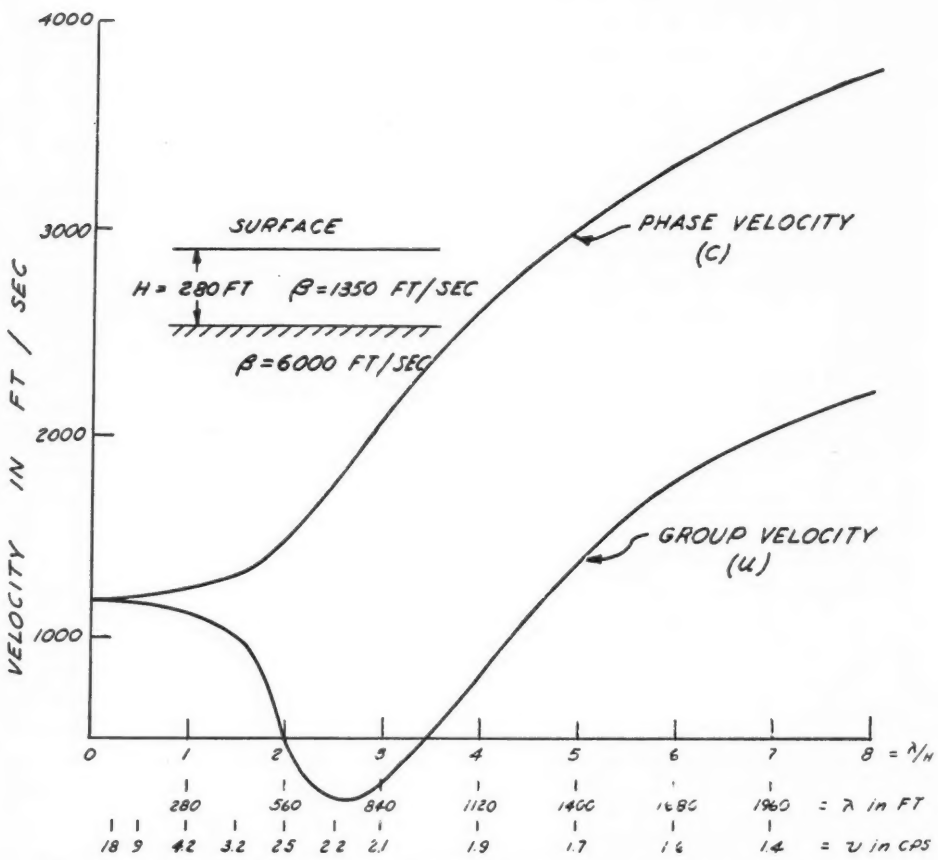


FIG. 13. Calculated Rayleigh wave dispersion curves (based on Sezawa's theory) for layering observed in Cap Rock area. $\beta$ is shear velocity.

from flexural vibration of the surface layer, acting as a rigid plate, overlying an incompetent, effectively liquid substratum (Ewing and Crary, 1934).

The most likely explanation for the unusual dispersive properties of these waves follows directly from classical wave theory. When the shots are at a depth of 150 ft, the uppermost layer, only 30 ft thick, hardly enters into the picture because the excitation is so far below its bottom. Neglecting this layer, we have a conventional two-layer situation, where the top layer has a lower speed than the substratum. Here, the upper medium comprises the low-speed sands and gravels extending from the base of the cap rock at 30 ft to the pronounced shear discontinuity at about 280 ft. The compressional discontinuity at the water table, 85-ft deep, does not affect the Rayleigh wave dispersion, which is controlled only by the shear-speed layering.

The dispersion curve to be expected in this case should be of the conventional

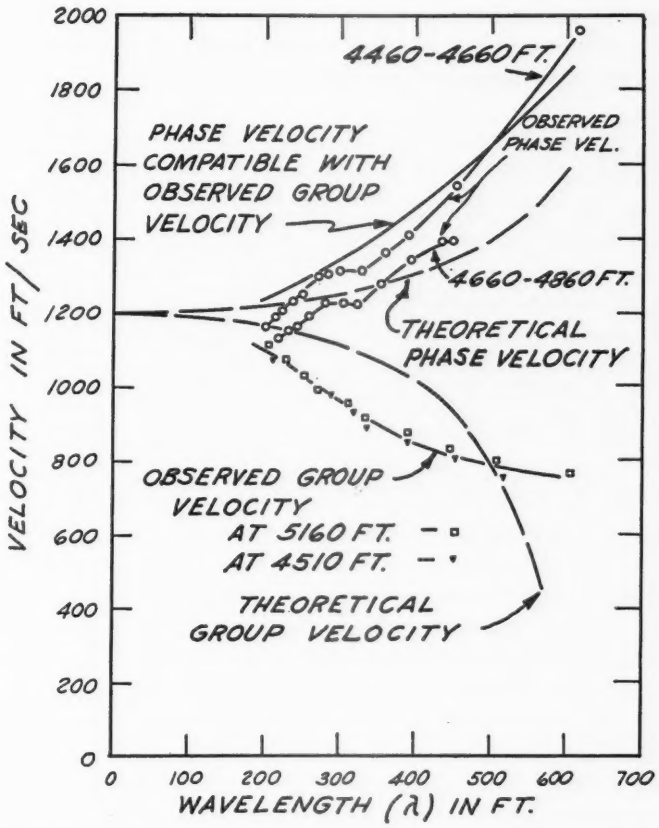


FIG. 14. Observed group and phase velocities for Rayleigh waves compared with theoretical curves from Fig. 12. Phase velocities determined by Fourier analysis. Group velocities measured directly from records.

type for a single low-speed surface layer. Using the results of theoretical calculations by Sezawa (1927), we can draw a dispersion curve for a two-layer solid, with the upper layer 280-ft thick, having a shear speed of 1,350 ft/sec in this layer and an average shear speed of 6,000 ft/sec in the substratum. Figure 13 shows the group and phase velocity curves computed on this basis. The abscissa scale is shown in terms of wavelength over layer thickness, wavelength for a 280-ft layer, and frequency.

From the frequency scale, it is immediately evident that any instrumental system having a low-frequency cut-off of 4 or 5 cps can record only those waves corresponding to the left-hand portion of the curves. If any lower frequencies are excited, they would not be seen on the records. This means that in the portion of the Rayleigh wave spectrum which the instrumental system would pass, the group velocity decreases with increasing period. In most locations, especially

where the weathered zone controls dispersion, the surface layer is considerably thinner compared to wave length, the recorded frequency region falls to the right of the group velocity minimum, and group velocity increases with increasing period.

Figure 14 shows the dispersion as measured on some records from the 150-ft shots. The phase velocity curves were determined by Fourier analysis and the group velocity data by direct measurement of arrival times of the Rayleigh wave cycles covering the range of periods from 0.145 to 0.320 seconds. Superimposed on the observed data are the pertinent portions of the theoretical curves shown in Figure 13. The agreement appears to support the hypothesis that the reverse dispersion is caused by a surface layer exceptionally thick in comparison with the wavelength corresponding to the cut-off frequency of the instrumental system.

Reverse dispersion of Rayleigh waves has been reported twice in the recent literature. Press and Ewing (1954) have described inversely dispersive, very long period Rayleigh waves on records made at the Seismological Laboratory in Pasadena from several large earthquakes, including the great Assam earthquake of August 15, 1950. These waves are explained on the basis of a very thick surface layer extending several hundred kilometers beneath the earth's crust into the mantle below. The continuous increase of shear velocity known to exist below the crust would have the same effect on Rayleigh wave dispersion as a discrete layer of the type assumed. Howell, Neuenschwander, and Pierson (1953) of Humble have recorded some inversely dispersive surface waves in the Gulf Coast region over the period range below 0.2 seconds with instruments somewhat similar to those we used. Their records showed waves with high-frequency and low-frequency dispersion occurring within the same time interval, so that the inverse dispersion is not as conspicuous to the eye as on the records reported in the present paper. Unfortunately, they did not have sufficient information on near-surface lithology to compare the data quantitatively with predictions based on wave theory.

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GEOPHYSICS, VOL. XIX, NO. 4 (OCTOBER, 1954), PP. 716–721, 2 FIGS.

# COMPARISON OF BREAK-POINT AND TIME-INTERCEPT METHODS IN REFRACTION CALCULATIONS*

N. N. ZIRBEL†

## ABSTRACT

This paper compares two methods of calculating depths from refraction data where the subsurface consists of a series of horizontal layers with velocities $V_0 < V_1 < V_2$, etc.

Equations are developed for calculating depths from the horizontal distances to the intersections of the various segments of the time-distance graph (the break-points). Examples are worked out to show that the error in depth due to an uncorrected change in thickness of the weathered layer is much less when the depths are calculated from break-points than when they are calculated from time-intercepts. In many areas weathering corrections should be unnecessary if the depths can be calculated from the break-points by the method outlined here.

## INTRODUCTION

The purpose of this paper is to outline a method by which the depths to refracting layers can be determined from the horizontal distances between the shot position and the intersections of the various segments of the time-distance graph. It will be shown that the depths so calculated are much less affected by variations in the thickness of the weathered layer than are depths calculated by a time-intercept method.

The equations used to calculate the depths from the $x$ intercepts of the break-points are derived first; examples are then worked out to show that the error in depth due to an uncorrected change in thickness of the weathered layer is much less when the depths are calculated using the break-point method than when they are calculated using a time-intercept method.

## DERIVATION OF EQUATIONS

Figure 1 shows the time-distance graph for horizontal layers of velocity $V_0$, $V_1$, $V_2$, etc., and corresponding thicknesses $h_0$, $h_1$, $h_2$, etc., where $V_0 < V_1 < V_2$, etc.

Then

$$t_0 = x_0/V_0 \tag{1}$$

$$t_1 = x_1/V_1 + (2h_0/V_0)\cos\phi_{01} \tag{2}$$

$$t_2 = x_2/V_2 + (2h_0/V_0)\cos\phi_{02} + (2h_1/V_1)\cos\phi_{12} \tag{3}$$

where $t_n$ is the time required for the wave penetrating to and traveling along the top of the layer with velocity $V_n$ to reach the point $x_n$ on the surface, and $\phi_{mn} = \sin^{-1} V_m/V_n$ (Nettleton, 1940, p. 251–255; Dix, 1952, p. 245–247).

Now at the intersection of the $V_0$ and $V_1$ lines, $x_0 = x_1 = x_{01}$ and $t_0 = t_1 = t_{01}$, or

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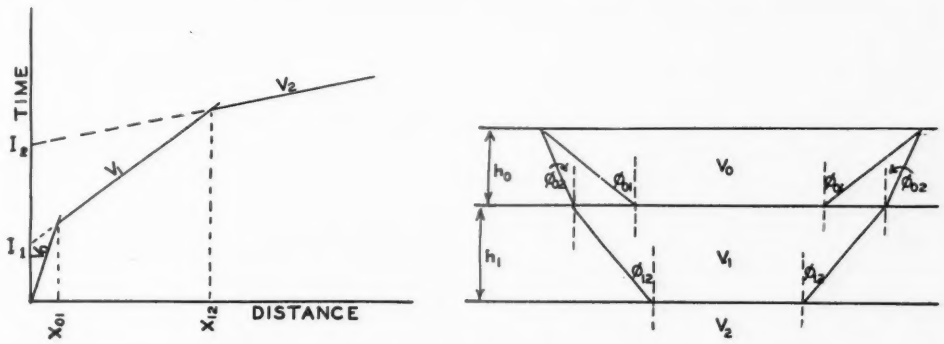


FIG. 1. Time-distance graph and vertical cross-section for general three-layer case.

from equations (1) and (2)

$$x_{01}/V_0 = x_{01}/V_1 + (2h_0/V_0)\cos\phi_{01}. \tag{4}$$

Substituting

$$\cos\phi_{01} = \sqrt{1 - \sin^2\phi_{01}} = \sqrt{1 - V_0^2/V_1^2}$$

and solving for $h_0$ gives

$$h_0 = x_{01}(1/2)\sqrt{(V_1 - V_0)/(V_1 + V_0)} = x_{01}K_{01}, \tag{5}$$

where

$$K_{pq} = (1/2)\sqrt{(V_q - V_p)/(V_q + V_p)}.$$

Now at the intersection of the $V_1$ and $V_2$ lines, $x_1 = x_2 = x_{12}$, $t_1 = t_2 = t_{12}$, and from equations (2) and (3),

$$h_1 = x_{12}(1/V_1 - 1/V_2)(V_1/2\cos\phi_{12}) + (2h_0/V_0)(\cos\phi_{01} - \cos\phi_{02})(V_1/2\cos\phi_{12}).$$

Substituting

$$\cos\phi_{12} = \sqrt{1 - V_1^2/V_2^2} = \sqrt{(V_2^2 - V_1^2)/V_2^2}$$

in the first term and $V_1/V_0 = 1/\sin\phi_{01}$ in the second term gives

$$h_1 = x_{12}(1/2)\sqrt{(V_2 - V_1)/(V_2 + V_1)} + h_0(\cos\phi_{01} - \cos\phi_{02})/(\sin\phi_{01}\cos\phi_{12}) \tag{6}$$

or

$$h_1 = x_{12}K_{12} + h_0M_{02}, \tag{7}$$

where

$$M_{pq} = (\cos\phi_{p(q-1)} - \cos\phi_{pq})/(\sin\phi_{p(q-1)}\cos\phi_{(q-1)q}).$$

This can be extended to any number of layers as

$$h_n = x_{n(n+1)}K_{n(n+1)} + h_0M_{0(n+1)} + h_1M_{1(n+1)} + \cdots + h_{(n-1)}M_{(n-1)(n+1)}. \quad (8)$$

Now consider the error introduced by neglecting the uppermost, or "weathered," layer (*i.e.*, by letting $h_0=0$).

From equation (3) at $x_2=0$ and $t_2=I_2$,

$$h_1 = \frac{I_2V_1}{2\sqrt{1 - V_1^2/V_2^2}} - h_0\frac{V_1}{V_0}\frac{\sqrt{1 - V_0^2/V_2^2}}{\sqrt{1 - V_1^2/V_2^2}},$$

which is the thickness of the $V_1$ layer as computed by the time-intercept method. The error due to neglecting the weathering is given by the second term on the right hand side.

From equation (6) at $x=x_{12}$,

$$h_1 = \frac{x_{12}}{2}\sqrt{\frac{V_2 - V_1}{V_2 + V_1}} + h_0\frac{(\sqrt{1 - V_0^2/V_1^2} - \sqrt{1 - V_0^2/V_2^2})}{(V_0/V_1)\sqrt{1 - V_1^2/V_2^2}},$$

which is the thickness of the $V_1$ layer as computed by the break-point method;

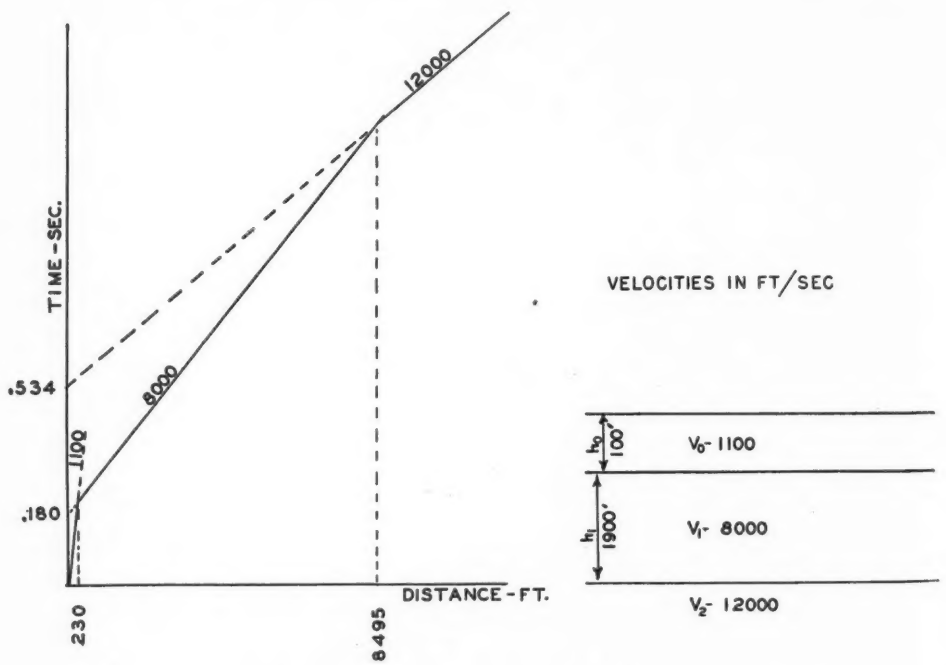


FIG. 2. Time-distance graph and vertical cross-section of three-layer configuration used in sample calculations.

the error due to neglecting the weathering is again given by the second term on the right hand side.

Now the ratio of these errors is

$$R = \frac{\text{error in break-point method}}{\text{error in time} - \text{intercept method}}$$

$$R = \frac{\sqrt{1 - V_0^2/V_1^2} - \sqrt{1 - V_0^2/V_2^2}}{-\sqrt{1 - V_0^2/V_2^2}} = 1 - \sqrt{\frac{1 - V_0^2/V_1^2}{1 - V_0^2/V_2^2}}.$$

Since $V_0 < V_1 < V_2$, $R$ is always greater than zero and less than one; and where $V_0$ is small compared to $V_1$ and $V_2$, the ratio $R$ is small.

This means that the error in computed depth due to neglecting the weathering is always less where the break-point method is used instead of the time-intercept method, and the error may be much less if the weathering is a thick layer of very low velocity.

The following numerical example, which illustrates the relationship just derived, is based on the configuration shown on the right hand side of Figure 2, the points shown on the $t$-$x$ graph having been calculated from equations (1), (2), and (3). The depth to the third layer will be calculated by the time-intercept and the break-point methods respectively, assuming 1) the configuration as indicated in Figure 2 and 2) absence of the uppermost ("weathered") layer.

### COMPARISON OF CALCULATED DEPTHS TAKING WEATHERED LAYER INTO ACCOUNT

We shall first calculate the depths by the time-intercept method and the break-point method respectively, using the complete $t$-$x$ graph and we shall compare the accuracy of both methods where all layers shown in Figure 2 are present.

Let us first apply the time-intercept method, using the following data:

$$V_0 = 1{,}100 \text{ ft/sec}, \qquad V_1 = 8{,}000 \text{ ft/sec}, \qquad V_2 = 12{,}000 \text{ ft/sec}.$$

$$I_1 = .180 \text{ sec}, \qquad I_2 = .534 \text{ sec}.$$

$$\sin \phi_{01} = 0.1375; \qquad \cos \phi_{01} = 0.9905$$

$$\cos \phi_{12} = 0.7453; \qquad \cos \phi_{02} = 0.9985.$$

From equation (2) at $x_1 = 0$, $t_1 = I_1$,

$$h_0 = I_1 V_0 / 2 \cos \phi_{01} = (.180 \times 1{,}100)/(2 \times 0.9905) = 100 \text{ ft}, \tag{9}$$

so that the error in $h_0$ is 0 ft.

From equation (3) at $x_2 = 0$, $t_2 = I_2$,

$$h_1 = (I_2 V_1)/(2 \cos \phi_{12}) - (h_0 V_1 \cos \phi_{02})/(V_0 \cos \phi_{12}) \tag{10}$$

$$= (.534 \times 8{,}000)/(2 \times 0.7453) - (100 \times 8{,}000 \times 0.9958)/(1{,}100 \times 0.7453)$$

$$= 1{,}903 \text{ ft},$$

so that the error in $h_1$ is 3 ft.

Calculating depths by the break-point method, we use the following data:

$$x_{01} = 230 \text{ ft}, \qquad x_{12} = 8{,}495 \text{ ft},$$

$$K_{01} = (1/2)\sqrt{(8{,}000 - 1{,}100)/(8{,}000 + 1{,}100)} = 0.4354$$

$$K_{12} = (1/2)\sqrt{(12{,}000 - 8{,}000)/(12{,}000 + 8{,}000)} = 0.2236$$

$$M_{02} = (0.9905 - 0.9958)/(0.1375 \times 0.7453) = -0.0517.$$

From equation (5),

$$h_0 = x_{01}K_{01} = 230 \times 0.4354 = 100 \text{ ft},$$

so that the error in $h_0$ is 0 ft.

From equation (7),

$$h_1 = x_{12}K_{12} + h_0M_{01} = 8{,}495 \times 0.2236 - 100 \times 0.0517 = 1{,}895 \text{ ft}$$

and the error in $h_1$ is 5 ft.

From the calculations above it can be seen that either method will give good results where the thickness and velocity of the weathered layer can be accurately determined.

## COMPARISON OF CALCULATED DEPTHS WHEN THE WEATHERED LAYER IS IGNORED

We shall next apply the time-intercept method assuming $h_0=0$, $I_1=0$, *i.e.*, ignoring the presence of the weathered layer.

From equation (10),

$$h_1 = I_2V_1/2 \cos \phi_{12} - 0$$

$$h_1 = (.534 \times 8{,}000)/(2 \times 0.7435) - 0 = 2{,}867 \text{ ft},$$

so that the error is the thickness of $h_1$ is 967 ft and the error in the depth of the $V_2$ layer is 867 ft. Now calculating depths by the break-point method with $h_0$ and $X_{01}$ still assumed to be zero, we use equation (7):

$$h_1 = x_{12}K_{12} + 0 = 8{,}495 \times 0.2236 = 1{,}899 \text{ ft},$$

so that the error in thickness of $h_1$ is 1 ft and the error in depth of the $V_2$ layer is 101 ft.

These figures are to be compared with the error in thickness of 967 feet and error in depth of 867 feet obtained when the time-intercept method was used with the same assumptions.

## APPLICATIONS

In normal field operations the shot will be below the weathering and the errors above will be cut in half. In most areas the variations in weathering thickness are small enough that it should be unnecessary to shoot weathering shots when the break-point method can be used to calculate the depths.

In using the break-point method, care must be taken to pick a true intersection between two velocities and not velocity breaks due to surface effects or due to an erroneous interpretation of a velocity which increases uniformly with depth as two velocities. Near a true intersection, the two separate waves can be observed on the records and the characteristic interference pattern as they meet and cross is a valuable guide in picking the break-point.

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GEOPHYSICS, VOL. XIX, NO. 4 (OCTOBER, 1954), PP. 722–738, 8 FIGS.

# THE METHOD OF CAGNIARD IN SEISMIC PULSE PROBLEMS*

C. HEWITT DIX†

## ABSTRACT

The main procedures used by L. Cagniard to calculate seismic pulse motion have been carried through for the case of a point source in an infinite medium. This relatively simple case serves as a basis for a simplified exposition of Cagniard's method. By using this case, we avoid cluttering the exposition with a large collection of algebraic details that tend to befog the main issues.

## INTRODUCTION

In a very remarkable book, Professor L. Cagniard (1939) has given a theory of the propagation of seismic pulses in two homogeneous media separated by a plane non-slipping boundary. The mathematics involved in this book is, in many instances, so difficult and complicated as to render the book inaccessible to a great many readers that really need to understand the material in it. It has been suggested to me by quite a number of geophysicists that a simplified exposition of Cagniard's method would be of value to the profession. I have therefore undertaken to present in as brief a manner as possible the essential features of Cagniard's method, limiting myself to the very simplest aspects of this theory.

In addition to a simple exposition of Cagniard's method, certain alternative approaches to the problems which he attacks may be suggested. These approaches can be carried through in a very simple case treated below, but they prove exceedingly difficult to follow in the general case treated by Cagniard.

It is assumed that the reader has a knowledge of such fundamental aspects of the theory of functions of a complex variable as Cauchy's integral theorem and Cauchy's integral formula. These matters are treated in any book on complex variable theory, but the reader who is not familiar with them will find a very brief and reasonably clear account of these matters in Webster (1950, p. 406–413).

Any subject of this sort reaches back into the investigator's background in so many different directions that it is quite difficult to be sure that nothing essential is missing. Perhaps the ideal procedure would be to make an explicit list of the assumptions which are made, and then make a strictly logical deduction of all results starting from the assumptions. This I might refer to as the Cartesian method. It is the method generally used by mathematicians.

I shall not use the Cartesian method, as I suppose that the readers will not, for the most part, be entirely happy using it. Instead, I shall use the method of A. N. Whitehead (1949, p. 27–32). According to the method of Whitehead, we first take an over-all look at our territory of investigation without really

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understanding the details at all. After we have seen the territory as a whole, we then look into certain details. This latter investigation, our second stage, we might call the first stage of precision. The very first look, Whitehead terms the stage of romance, in which the ideas remain entirely fuzzy. After the first stage of precision, where we get a few precise ideas, we take a look back at the original structure and view it with a little sharper focus. But we realize in this latter stage, the third stage, which is the first stage of synthesis, that we are not getting a completely precise view of the situation, and so we go on to the second stage of precision, in which we sharpen our focus on certain matters previously left unattended.

Whitehead's method of procedure is not a perfectly well defined one as is Descartes', but it has the great advantage that it corresponds to the kind of human activity that most of us are capable of carrying through. And so I am following it, in broad outline, in the exposition below.

## THE PHYSICAL PROBLEM

We shall suppose that we have a pressure source in a spherical cavity separated from a plane reflector. This may correspond to a buried source at a depth, $h$, below a free surface, in which we remove the very small effect of the atmosphere and replace the atmosphere by a vacuum. When a pressure is applied in the spherical cavity, it generates a disturbance in the surroundings. The disturbance travels outwards, as we all know, so that it will affect an instrument located at any point in the medium according to the registering properties of that instrument. Let us suppose that we have a sufficient number of instruments so that we can determine the displacement at every point in the medium. This of course is a ridiculous idealization, but let us suppose it, anyway.

Now we may take the summary look at the method of Cagniard as outlined below. In order to carry through Cagniard's method, we make use of the following steps:

(1) We suppose that for a given source and a given point of observation at a time $t$, there will be a vector displacement of the particle of the medium at the point $P$, which we denote by $\mathbf{u}(P, t)$.

(2) This displacement forms a vector field to which we can apply the method of Helmholtz to derive two new fields $\psi$ and $\mathbf{U}$, satisfying the relation

$$\mathbf{u}(P, t) = \text{grad } \psi + \text{curl } \mathbf{U}; \tag{1}$$

$\psi$ will represent the longitudinal wave and $\mathbf{U}$ will represent the transverse wave.

(3) The equations of motion, that is the Newtonian equations describing the motion of the masses, can be written in terms of the potentials $\psi$ and $\mathbf{U}$.

(4) The conditions of continuity at the free surface or at the interface can be also written in terms of $\psi$ and $\mathbf{U}$.

(5) One can put a particular signal in the cavity corresponding to a unit step

in $\psi$ or better $\psi = 1(t-r/V)/r$ where $1(\tau)$ is zero for $\tau < 0$ and is one for $\tau > 0$ (this is a mathematical trick which simplifies many further considerations).

(6) The equations of motion, the equations of conditions at the interface, and the form of the source can all be transformed by the method of Laplace; that is, we make the Laplace transform of the whole problem. Examples of Laplace transforms are:

$$X(\rho, z; p)/p = \int_0^\infty e^{-pt}\psi(\rho, z; t)dt, \tag{2}$$

$$\mathbf{Y}(\rho, z; p)/p = \int_0^\infty e^{-pt}\mathbf{U}(\rho, z; t)dt. \tag{3}$$

(7) When this is done, the equations of motion can be solved by the method of separation of the variables and these solutions can be combined in such a way as to satisfy both the initial or source condition and the condition of continuity at the boundary.

(8) Cagniard has discussed these solutions mathematically and has shown that they are unambiguous and so can be utilized.

(9) Our problem now is to find the inverse transformation of our Laplace transform, namely (a) $A(\rho, z; t)$ the $\psi$-response at the point $(\rho, z)$, at the time $t$, to the input unit step $\psi$ and (b) $B(\rho, z; t)$, the $\mathbf{U}$-response at the point $(\rho, z)$, and the time $t$, to the unit step $\psi$. (We might even imagine that it is possible physically to have an input step $\psi$ and also to record at the point $(\rho, z)$ the $\psi$-response and the $\mathbf{U}$-response by special instruments responsive to $\psi$ and to $\mathbf{U}$ individually; although this is physically not possible at the moment, it is quite possible to imagine it.)

(10) When we apply the gradient and the curl as indicated in step (2) above, we derive the displacement vector from our potentials.

(11) By using the integral of Duhamel (Dix, 1952, p. 374–378) we can get the displacement corresponding to any input pressure.

Let the above list of 11 steps constitute our first rather blurred view of the situation. We shall refer to them as STEPS in the sequel. We know in a general way that we want to be able to put in a pressure in a spherical cavity and get out the variation of displacement at any point in the medium.

### THE FIRST STAGE OF PRECISION, A CLOSER VIEW OF THE SOURCE

Let us make our view of the source a little more precise, supposing that we have a spherical cavity in a perfectly elastic homogeneous isotropic elastic medium. Let us furthermore suppose that until a time $t = 0$ nothing has happened. Then let nothing continue to happen until a time $t_0$, at which a longitudinal wave would reach the boundary of the cavity from the center, the radius of the cavity being $a$. This would be at a time, $t_0 = a/V$. Let $\tau = t - r/V$. Then we find that if a pressure $P_0$ is suddenly applied at the time $t_0 = a/V$ and held for all remaining

time, then the $\psi$-potential, in this case assuming no interface boundary, is given by

$$\psi(r, t) = 0 \text{ for } t < r/V \quad \text{or} \quad \tau < 0, \tag{4}$$

$$= \frac{P_0 a^3(2+S)}{4\sigma r V^2}\left[-1 + \left(\frac{2+S}{1+S}\right)^{1/2} e^{-\kappa\tau}\cos\left[\gamma\tau - \tan^{-1}(1+S)^{-1/2}\right]\right]$$

$$\text{for } \tau > 0, \tag{5}$$

where $\kappa = 2V/[a(2+S)]$, $\gamma = \kappa(1+S)^{1/2}$, $\bar{\sigma}$ is Poisson's ratio, $S = \lambda/\mu$, $\mu$ and $\lambda$ are the Lamé elastic constants, $V^2$ is the square of the longitudinal wave velocity, $\sigma$ is the density, and $r$ is the radial distance from the center of the cavity out to the point where the measurement of the potential is made. This equation has been derived by F. G. Blake (1952). Knowing this response to an input step pressure we can derive the response to any input pressure, $\pi(t)$, by means of the Duhamel integral (Dix, 1952, p. 374–378) of STEP (9). Equations (4) and (5) gives us the potential, from which we can derive the displacement corresponding to *any* input pressure. So, if we can do all of the operations indicated in the summary of Cagniard's method, we can solve the problem corresponding to any input pressure, deriving the displacement generated by this at any time merely by taking the gradient of $\psi$ and the curl of $\mathbf{U}$ as indicated in equation (1), which is in STEP (2) of the summary above. Leaving aside for now the effect of the interface, we do not consider $\mathbf{U}$.

What we have just developed above is a process for making more precise the meanings of STEP (1).

In order to secure a more precise view of STEP (2), it is suggested that the reader refer to H. B. Phillips (1933, p. 186–187) where the decomposition due to Helmholtz is carried out in some detail. In reading this reference, it is best to regard the procedure as only an example of a Helmholtz decomposition. Phillips goes forward by positive steps and shows that a decomposition can be carried out. However, he does not show that this decomposition is the only one possible. Many others are also possible. To see this, it is only necessary to add to the one which is derived in Phillips the expression

$$0 = \text{grad } \psi_0 + \text{curl } \mathbf{U}_0. \tag{6}$$

Let us return to the input step $\psi$ used in STEP (5) above. We could take this solution of the $\psi$ equation in spherical polar coordinates and convert it to cylindrical coordinates, which we are going to need on account of the symmetry conditions of our problem. However, instead of doing this, let us consider the equation for $\psi$ in cylindrical coordinates, which is part of STEP (3). This gives

$$\frac{\partial^2\psi}{\partial\rho^2} + \frac{1}{\rho}\frac{\partial\psi}{\partial\rho} + \frac{\partial^2\psi}{\partial z^2} = \frac{1}{V^2}\frac{\partial^2\psi}{\partial t^2}. \tag{7}$$

Now let us carry out the Laplace transform as indicated in STEP (6). On the left side of (7) we simply get a repetition of practically the same expression, but when we come to the derivative of $\psi$ with respect to $t$, we introduce a new situation. Let us transform $\partial\psi/\partial t$. We get

$$\int_0^\infty \frac{\partial\psi}{\partial t} e^{-pt}dt = [\psi e^{-pt}]_0^\infty - \int_0^\infty \psi e^{-pt}(-p)dt = p\int_0^\infty \psi e^{-pt}dt. \tag{8}$$

As we can clearly see by carrying out the partial integration, the differentiation with respect to time corresponds to multiplication of the transform of $\psi$ by $p$. We do this twice, so we get multiplication by $p^2$, and our Laplace-transformed equation is

$$\frac{\partial^2 X}{\partial\rho^2} + \frac{1}{\rho}\frac{\partial X}{\partial\rho} + \frac{\partial^2 X}{\partial z^2} - \frac{p^2}{V^2}X = 0. \tag{9}$$

This we solve by the method of separation of variables and get two equations giving us elementary solutions for $R(\rho)$ and $Z(z)$. Thus the elementary solutions of the Laplace transform equation are

$$R(\rho) = J_0(\lambda\rho), \qquad Z(z) = e^{\pm(\lambda^2+p^2/V^2)^{1/2}z}, \tag{10}$$

where we have to throw out the $Y_0$ Bessel function because of the fact that it is infinite all along the $\rho=0$ axis. $\lambda$ is an arbitrary parameter.

Now let us remember that our equations are linear: that is to say, the sum of any two solutions is a new solution. Generalizing this process, we try to form an integral sum in order to represent our spherically symmetric source in cylindrical coordinates by the relation

$$\int_0^\infty \frac{1(t - r/V)}{r} e^{-pt}dt = e^{-pr/V}/pr$$
$$= \int_0^\infty F(\lambda)J_0(\lambda\rho)e^{-(\lambda^2+p^2/V^2)^{1/2}z}d\lambda, \tag{11}$$

where we take the origin at the center of our cavity source; $z$ is supposed positive, and $F(\lambda)$ has yet to be determined. There is a process for determining it (Sommerfeld, 1949, p. 109–110, equation (8a)), but as we wish to keep all matters on a relatively elementary level, let us anticipate just a little bit what this formula will be. It is

$$F(\lambda) = \lambda/[p(\lambda^2 + p^2/V^2)^{1/2}]. \tag{12}$$

This can be readily verified by taking $\rho=0$ which makes $J_0(0)$ equal to 1, so that our relationship is

$$\int_0^\infty \frac{\lambda e^{-(\lambda^2+p^2/V^2)^{1/2}z}}{(\lambda^2 + p^2/V^2)^{1/2}}d\lambda = \frac{1}{2z}\int_{\lambda=0}^\infty \frac{e^{-(\lambda^2+p^2/V^2)^{1/2}z}}{(\lambda^2 + p^2/V^2)^{1/2}z} d[(\lambda^2 + p^2/V^2)z^2]$$
$$= e^{-pz/V}/z, \tag{13}$$

by direct integration. So we know that along the $\rho=0$ axis, equation (12) is correct.

Now we are going to establish the fact that our formula is generally correct for any $\rho$ by just writing it out and showing that this leads us back to our original step input. In carrying out this work we shall follow Cagniard's procedure step by step and references will be given as we go along so that the analogy can be closely followed if the reader wishes to. What follows then may be taken as a skeleton outline of the work that Cagniard carried through in the fifth chapter of his book. Incidentally, in carrying out this procedure we shall verify the fundamental formula which is the first formula of section 16 of Chapter 4 of Cagniard's book.

So we start with relations (11) and (12). We ultimately wish to come back to the step function $1(t-r/V)/r$. Thus

$$\frac{e^{-pr/V}}{pr} = \int_0^\infty \frac{uJ_0(pu\rho)e^{-p(u^2+S^2)^{1/2}z}du}{(u^2+S^2)^{1/2}} = \int_0^\infty e^{-pt}A_s(\rho, z; t)dt \qquad (14)$$

corresponds to equation (1) in Cagniard's Chapter 5. We have introduced the substitutions $\lambda=pu$ and $1/V=S$.

Next we must use his equation (3), at least the first part of it. This is

$$J_0(z) = \frac{1}{\pi}\int_0^\pi e^{-iz\cos\omega}d\omega. \qquad (15)$$

For those unfamiliar with this particular formula for the Bessel function, it is suggested that the easiest and most elementary way to prove it is to expand the exponential as a power series in $iz\cos\omega$ and integrate term by term. Observe that the odd-powered terms drop out and that the even-powered terms can be evaluated (Peirce, 1910, p. 62, Formula 483). Carrying out this operation, observe that one obtains the power series for $J_0(z)$. It is supposed that the reader is familiar with this most elementary property of the Bessel function, its power series (Jahnke and Emde, 1945, p. 128). Perhaps we could use the expression (15) just as it stands, but we observe that Cagniard transforms this to another form. If the reader wishes to know the reason for this transformation, he will easily find it by trying not to make it. In other words, if he carries through the process below using formula (15), he will soon find that he gets into a certain amount of difficulty owing to the fact that he has to deal with double-valued functions on a Riemann-surface. In order to avoid this complication we follow Cagniard and make the following transformation. We expand the exponential in (15) into the real and imaginary parts; thus

$$J_0(z) = \frac{1}{\pi}\int_0^\pi \cos(z\cos\omega)d\omega - \frac{i}{\pi}\int_0^\pi \sin(z\cos\omega)d\omega. \qquad (16)$$

Then we note that the integrands can be shown graphically. In Figure 1, (a)

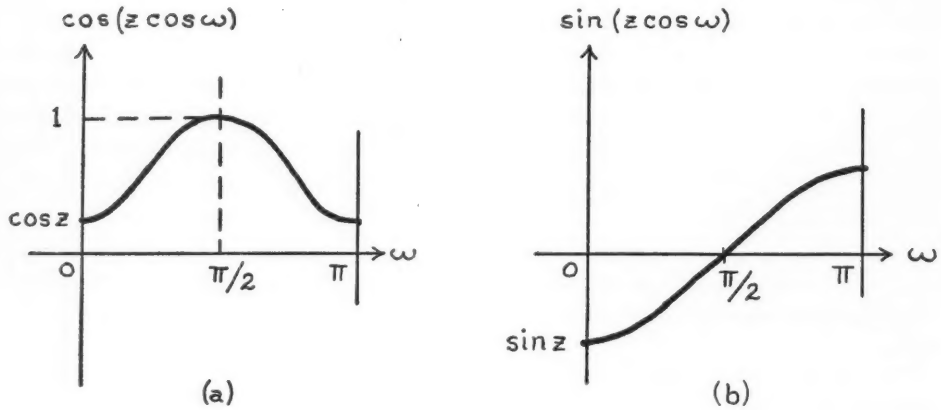


FIG. 1

represents the real part and (b) the imaginary part. Clearly the imaginary part has a zero integral but the real part is symmetrical about the center of the range and so we can rewrite the integral as (Cagniard, 1939, p. 55, equation (3))

$$J_0(z) = \frac{2}{\pi}\int_0^{\pi/2} \mathcal{R}[e^{-iz\cos\omega}]d\omega. \tag{17}$$

This expression we are now ready to substitute in equation (14) to express the Bessel function there in terms of the integral with respect to $\omega$. This gives us (Cagniard, 1939, p. 55, equation (4))

$$\frac{2}{\pi}\int_0^{\infty}\int_0^{\pi/2} \mathcal{R}[e^{-p(iu\rho\cos\omega+az)}]d\omega\,\frac{udu}{a}$$
$$= \frac{2}{\pi}\int_0^{\pi/2} \mathcal{R}\left[\int_0^{\infty} e^{-p(iu\rho\cos\omega+az)}\,\frac{udu}{a}\right]d\omega \tag{18}$$

where $a=+(u^2+S^2)^{1/2}$.

Looking back at expression (14), we see that if we make a transformation defined by

$$t' = i\rho u\cos\omega + (u^2+S^2)^{1/2}z \tag{19}$$

then we have some chance of changing the integral (18) into the form of the right hand side of equation (14) and this will be our objective. Thus we make the transformation (19) and obtain as a result the expression (Cagniard, 1939, p. 61, equation (15))

$$\frac{2}{\pi}\mathcal{R}\int_0^{\pi/2} d\omega\int_{H\omega} e^{-pt'}\,\frac{u}{a}\,\frac{\partial u}{\partial t'}\,dt'. \tag{20}$$

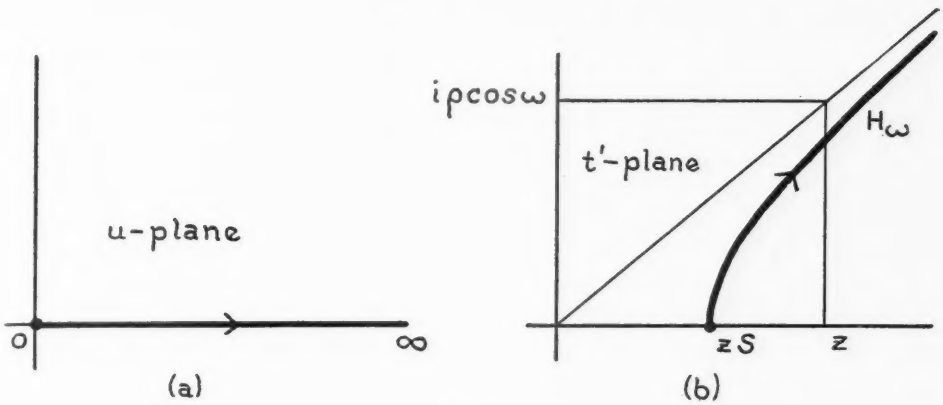


FIG. 2

Note that (Cagniard, 1939, p. 62, equation (16))

$$\frac{\partial u}{\partial t'} = \frac{1}{i\rho \cos \omega + uz/a}. \tag{21}$$

Now the only trouble with expression (20) is that the path of integration, $H_\omega$, is a sort of hyperbolic curve as illustrated in Figure 2(b), where $H_\omega$ is the transform in the $t'$-plane of the real path from zero to infinity in the $u$-plane shown in Figure 2(a). Because of the fact that $H_\omega$, the path in the $t'$-plane, depends upon $\omega$, it is necessary to make a small change. Referring to Figure 3(a), we see the path $H_\omega$ closed by means of a large arc of a circle and then a return path along the real axis except for the upward indentation at $t' = (\rho^2 \cos^2 \omega + z^2)^{1/2} S$. Now this large arc contributes nothing to the integral because of the fact that we have a negative exponential with an arbitrarily large negative real part. Also a study of the integrand of the inner integral will show that there are no singularities within this closed path and so we can apply Cauchy's integral theorem to the whole path, the result being that the integral around the whole path is 0. Thus we can rewrite integral (20) (Cagniard, 1939, p. 63, equation (17)) as

$$\frac{2}{\pi} \mathcal{R} \int_0^{\pi/2} d\omega \int_{zS}^{\infty} e^{-pt'} \left( \frac{u}{a} \frac{\partial u}{\partial t'} \right) dt', \tag{22}$$

it being understood that $t'$ makes the small indentation.

Why is it necessary to make this small indentation? This may be seen easily by studying the behavior of $\partial u/\partial t'$ from equation (21). This quantity is easily seen to be $\infty$ when

$$u = u_0 = \pm iS\rho \cos \omega / (\rho^2 \cos^2 \omega + z^2)^{1/2}, \tag{23}$$

and also when

$$t' = t_0' = S(\rho^2 \cos^2 \omega + z^2)^{1/2}. \tag{24}$$

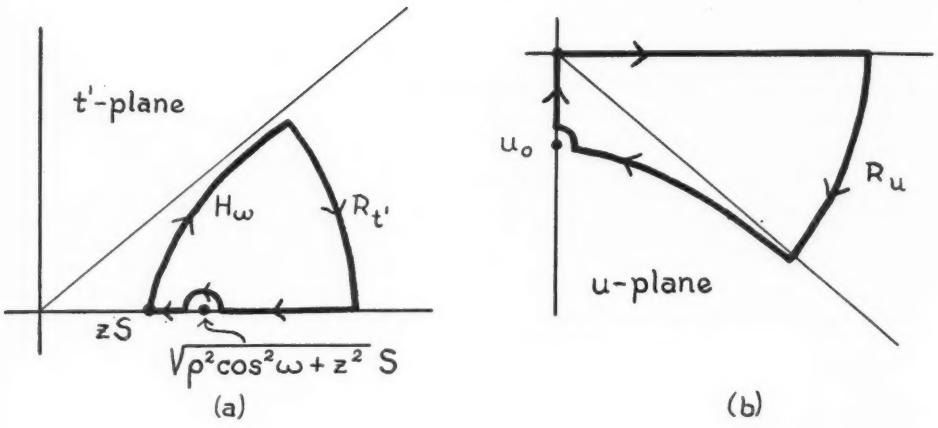


FIG. 3

These correspond to singular points of this derivative as shown on (a) and on (b) in Figure 3. Figure 3(b) thus shows the map of the closed circuit which we have just used. As we pass by the singularity in the $t'$-plane, we introduce a right-angle bend in the map in the $u$-plane on the negative imaginary axis as indicated. This singularity, which we have now introduced for the first time, is not one of a serious kind and it really gives no trouble. We only have to be careful to avoid it in making our closed contours; otherwise we cannot claim that we have no singularities within or on our contour and so we could not otherwise apply Cauchy's integral theorem in order to pass from the $\omega$-dependent path $H_\omega$, to the path almost independent of $\omega$ which we have achieved in the relation (22).

Our next procedure is to change the order of integration in equation (22) and get (Cagniard, 1939, p. 64, equation (20))

$$\int_{zS}^{\infty} e^{-pt'}\left[\frac{2}{\pi}\mathcal{R}\int_0^{\pi/2}\frac{u}{a}\frac{\partial u}{\partial t'}\,d\omega\right]dt'. \tag{25}$$

Thus we see that if we define $A$ as (Cagniard, 1939, p. 65, equation (21))

$$\left.\begin{aligned} A(\rho, z; t') &= 0 \quad \text{for} \quad t' < Sz \\ &= \frac{2}{\pi}\mathcal{R}\int_0^{\pi/2}\frac{u}{a}\frac{\partial u}{\partial t'}\,d\omega \quad \text{for} \quad t' > Sz, \end{aligned}\right\} \tag{26}$$

then in a certain sense we have solved our problem. We shall regard equation (26) as the *first form* of our solution.

Observe that if $\rho=0$, every term under the integral sign in equation (26) is independent of $\omega$, and so the integration can be easily carried out. This gives

$$A(0, z; t')_{t'>Sz} = \frac{2}{\pi}\mathcal{R}\left[\frac{u}{a}\frac{\partial u}{\partial t'}\right]\frac{\pi}{2} = \frac{1}{z}, \tag{27}$$

and verifies the fact that the solution is the unit step function divided by the distance from the source.

Generally speaking, this first Cagniard form is useful mainly in the case where we are right on the $\rho=0$ axis. It is also useful in the immediate neighborhood of this axis, since we can regard $\rho$ as an infinitesimal and so operate using the usual infinitesimal analysis, keeping quantities only of the order needed, usually of the first order. The above remarks apply equally well to the more complicated expressions involving reflections and refractions from either the free surface or from a plane boundary between two homogeneous media on the $\rho=0$ axis.

If one wishes, one can express the real part of the integral as the average of the integral and its complex conjugate thus:

$$A_{t'>zS} = \frac{1}{\pi}\int_0^{\pi/2} \left\{ \frac{u}{a}\frac{\partial u}{\partial t'} + \overline{\frac{u}{a}\frac{\partial u}{\partial t'}} \right\} d\omega. \tag{27'}$$

This has advantages in some instances.

Our next problem is to follow Cagniard in transforming this expression (26) to a new form which is more suitable for use when $\rho$ is not equal to 0. In order to do this we merely let the transformation (19) define a transformation from $\omega$ to $u$ while we hold $t'$ constant. Carrying out this transformation, we obtain from equation (26) (Cagniard, 1939, p. 65, equation (22))

$$A_{t'>zS} = \frac{2}{\pi}\mathcal{R}\int_{C_{t'}} \frac{u}{a}\frac{\partial u}{\partial t'}\frac{\partial \omega}{\partial u}\,du. \tag{28}$$

If we evaluate the derivative of $\omega$ with respect to $u$, we get (Cagniard, 1939, p. 65, equation (23))

$$\frac{\partial \omega}{\partial u} = \frac{i\rho\cos\omega + uz/a}{iu\rho\sin\omega}, \tag{29}$$

and the product of the derivatives is the simple expression

$$\frac{\partial u}{\partial t'}\cdot\frac{\partial \omega}{\partial u} = \frac{1}{iu\rho\sin\omega} = \frac{1}{i\{u^2\rho^2 + (t'-az)^2\}^{1/2}}. \tag{30}$$

Substituting this in equation (28), we get (Cagniard, 1939, p. 66, equation (24))

$$A_{t'>zS} = -\frac{2}{\pi}\mathcal{R}i\int_{C_{t'}} \frac{u\,du}{a\{(u^2\rho^2 + (t'-az)^2\}^{1/2}}. \tag{31}$$

If we further make use of the fact that the real part of $i$ times a complex number is merely minus the imaginary part of that number, or

$$\mathcal{R}i(\mathcal{R}z + i\mathcal{I}z) = -\mathcal{I}z,$$

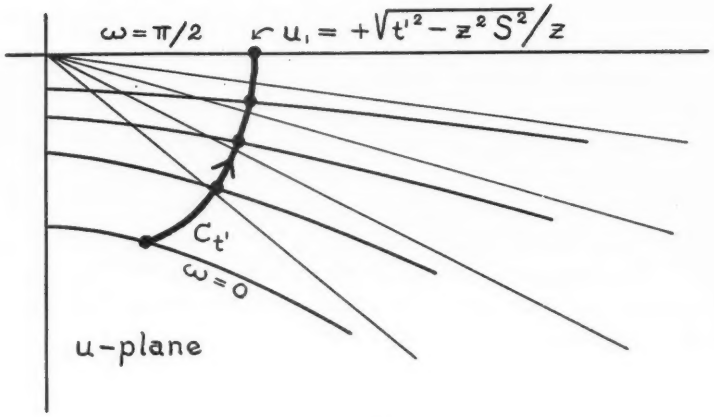


FIG. 4

then we get the expression (Cagniard, 1939, p. 67, equation (25))

$$A(\rho, z; t')_{t'>zS} = \frac{2}{\pi}\,\Im\int_{C_{t'}} \frac{udu}{a\{u^2\rho^2 + (t' - az)^2\}^{1/2}}. \tag{32}$$

We now must learn more about the properties of the curve $C_{t'}$ along which we are integrating. This is the curve in the $u$-plane which corresponds to holding $t'$ constant and allowing $\omega$ to vary from 0 to $\pi/2$. In Figure 4 I have redrawn Figure 3(b) to show asymptotes corresponding to various values of $\omega$ from 0 to $\pi/2$. Holding $t'$ constant, we pass from the point $\omega=0$ to $\omega=\pi/2$ as indicated. The details of this path are not difficult to work out quantitatively and they are left to the reader. There is some advantage here also in expressing the integral not as an imaginary term but as $1/2i$ times the difference between the integral and its complex conjugate; thus

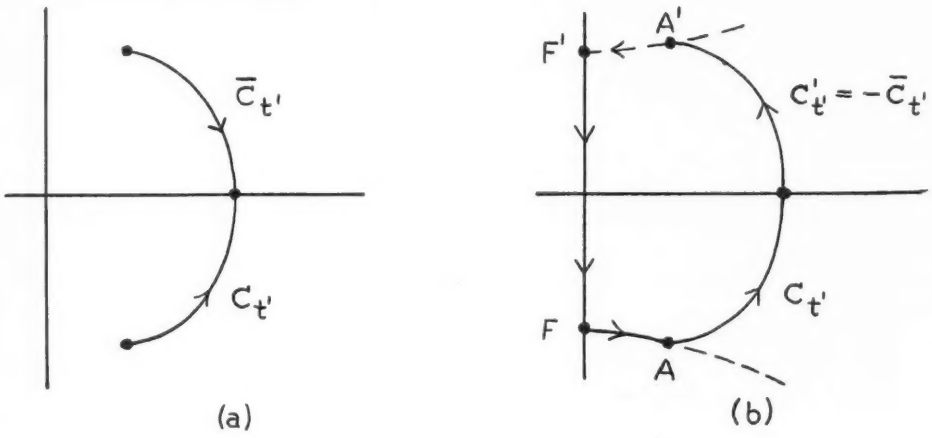


FIG. 5

$$A_{t'>zS}=\frac{1}{i\pi}\left[\int_{C_{t'}} \frac{udu}{a\{u^2\rho^2+(t'-az)^2\}^{1/2}}-\int_{\bar{C}_{t'}} \frac{\bar{u}d\bar{u}}{\bar{a}\{\bar{u}^2\rho^2+(t'-\bar{a}z)^2\}^{1/2}}\right], \tag{33}$$

where $C_{t'}$, and $\bar{C}_{t'}$ are illustrated in Figure 5(a). It is not difficult to see that the path in Figure 5(a) is related to the path in 5(b) which corresponds to the integral (Cagniard, 1939, p. 71, equation (28))

$$A_{t'>zS}=\frac{1}{i\pi}\int_{C_{t'}+C_{t'}'} \frac{udu}{a\{u^2\rho^2+(t'-az)^2\}^{1/2}}. \tag{34}$$

Notice that we now have the solution expressed as a single integral in the complex plane. There is a little difficulty in this expression due to the fact that the end points of the path (Figure 5(b)) are both singularities of the integrand since these are points at which the sin $\omega$ is 0. However, it may be shown without

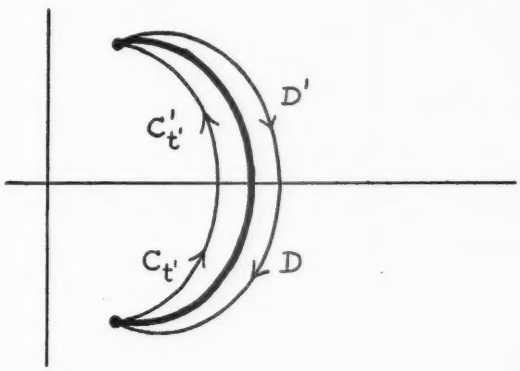


FIG. 6

much trouble that the integral is convergent at these points and the integration can be carried from one end of the path to the other. These points, however, do correspond to branch points of the integrand, that is to zeros of the radical in the denominator. We follow Cagniard by making the branch cut between these two branch points, as illustrated by the heavy curve in Figure 6. Having made this cut to keep the integrand single valued, we can then return by our path on the right side of the cut, as illustrated by $D'$, $D$. Then we find that the return path gives precisely the same value as the path $C_{t'}+C_{t'}'$. Consequently the value of the entire integral is the value of the integral along the closed path $C_{t'}+C_{t'}'+D'+D$, all divided by two. But if we wish, we can extend this path of integration, still staying in the same sheet of the $u$-surface, that is, on the same branch of the double valued integrand, by taking the path over to the branch cut between $Q$ and $Q'$ (these are the branch points where $a$ becomes double valued). We then go down along the imaginary axis on its right side to an arbitrarily large radius and then follow counterclockwise all the way around to the left side of the lower

imaginary axis. The remainder of the path around $Q$, $Q'$, and the moon-shaped curve, is shown in Figure 7. By doing this we make a circuit which encloses no singularities of the integrand. So by Cauchy's integral theorem the integral along this closed circuit is 0. Thus the integral along the moon-shaped part plus the integral around the branch cut $QQ'$ plus the integral around the infinite circle $R$, is 0. Now it is easily shown that the integral carried around the branch cut $QQ'$ is 0 as parts cancel out due to change in sign at the origin. Therefore the integral taken around the moon-shaped curve is just the negative of the integral taken around the infinite circle.

There is a little technical detail at this stage that has to be taken care of.

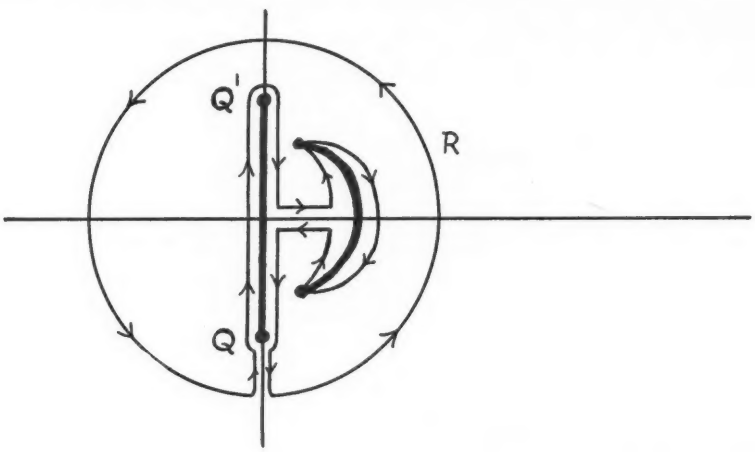


FIG. 7

The algebraic sign of the radical in the denominator of equation (34) is positive where the path of integration crosses the real $u$-axis (where $\omega=\pi/2$). If we let $u$ continuously increase along the real axis, this radical remains positive. But we have passed across the branch cut of Figure 6 and so we arrive in the neighborhood of infinity with the positive radical having the wrong sign. So in evaluating the integral around $R$ it is necessary to change the sign of the radical's denominator. Taking care of this sign change we have (Cagniard, 1939, p. 72, equation (29))

$$A(\rho, z; t')_{t'>zS} = \frac{1}{2\pi i} \lim_{R\to\infty} \int_R \frac{udu}{a(u^2\rho^2 + u^2z^2 + u^2S^2 + t'^2 - 2t'az)^{1/2}}$$

$$= + \frac{1}{(\rho^2 + z^2)^{1/2}}, \tag{35}$$

which is easily seen to be the step solution of our problem.

Our solution has just one little flaw: for $z/V<t'<(\rho^2+z^2)^{1/2}/V=r/V$ we must

have $A \equiv 0$. Thus we need to look at this matter a little more closely, since our discussion has left out something essential (Cagniard, 1939, p. 75–76).

Suppose $t' = +(\rho^2 c^2 + z^2)^{1/2} S$ with $0 < c < 1$. This is just a way of placing $t'$ between $zS$ and $rS$. Then from (19)

$$(\rho^2 c^2 z^2)^{1/2} S = i\rho u \cos\omega + (u^2 + S^2)^{1/2} z = \text{constant}$$

along the path $C_{t'}$. This implies that on $C_{t'}$

$$u = \frac{\rho S z (c^2 - \cos^2\omega)^{1/2}}{\rho^2 \cos^2\omega + z^2} - i\frac{\rho S \cos\omega (\rho^2 c^2 + z^2)^{1/2}}{\rho^2 \cos^2\omega + z^2}. \tag{36}$$

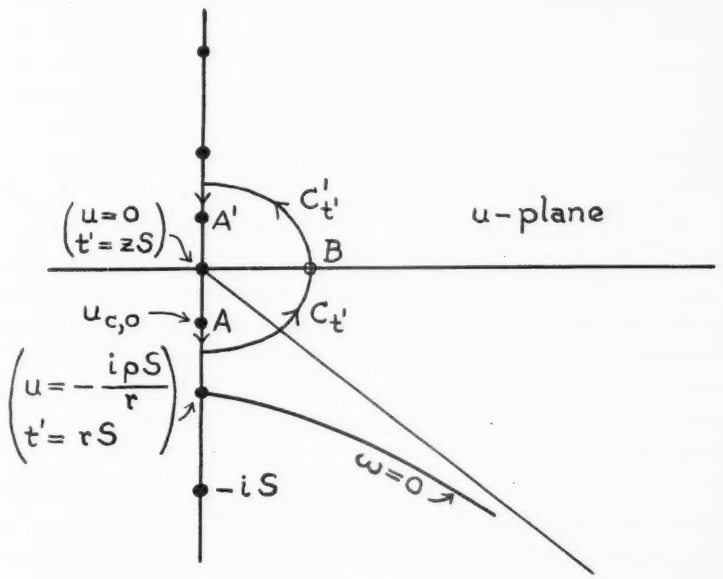


FIG. 8

But both parts of (36) are pure imaginaries for $\omega = 0$, the value of $u$ being then

$$-i\frac{\rho S}{r^2}\left\{(\rho^2 c^2 + z^2)^{1/2} - z(1 - c^2)^{1/2}\right\} = u_{c,0}. \tag{37}$$

Referring to Figure 8, $C_{t'}$ starts at $u_{c,0}$ on the negative imaginary axis and runs along the imaginary axis till $\cos\omega = c$. After this, it moves into the 4th quadrant, finally ending at $u_c\pi/2 = \rho c S/z$.

We can again extend the integration path from $C_{t'}$ to $C'_{t'}$ (see Figure 5(b)) as shown in Figure 8, giving the path $ABA'$. This latter path can be closed and since the integrand has no singularities within the closed path the closed path integral is zero. So the integral over $C_{t'} + C'_{t'}$ is the integral from $A$ to $A'$ along the imaginary axis of

$$\frac{u}{i\pi a\{u^2\rho^2 + (t' - az)^2\}^{1/2}}, \tag{38}$$

and the only quantity which changes sign on passing through the origin is $u$. $a$ and $u^2$ and the radical denominator are of one sign and have equal values for $\pm il = u$ within the imaginary range considered. Because of the changing sign of $u$ at $u=0$, the integral of equation (38) from $A$ to $A'$ along the imaginary axis is zero (Cagniard, 1939, p. 75–76).

This is the result that completes the investigation of this stage of precision as we can now correct equation (34) (and, working backwards, also equation (26)), replacing $zS$ by $rS$.

## SYNTHESIS

We have thus verified for the general case the expression representing the Laplace transform of the source which Cagniard has utilized in his work. We have carried out this verification using his own processes in detail.

The procedures that have been carried on above are the same as those carried on by Cagniard and therefore represent nothing new. They do however show his procedure in detail without the pain introduced by the very difficult algebra which he carries with it. Thus the essentials are brought into clearer relief.

The treatment above outlines Cagniard's method in most simple form. While still dealing with the simplest aspects, it may be valuable to look briefly at certain alternate procedures. One would only look at such alternates if one felt the method already available was unnecessarily complicated or if more useful alternate formulas might be gotten.

Certainly simpler procedures are available for the problem treated above, but the problem of their generalization to the more interesting reflection and refraction problem is not straightforward and simple (in principle!). However, the extension of the procedure above is simple in principle.

A most natural alternate approach would be via the standard inversion formula (Widder, 1946, p. 66) for the Laplace transform. However, one has to be extremely careful in dealing with the limit processes involved. I suspect the reason for this is that we are dealing with $1(t-r/v)$ and there is the easy possibility of introducing the Dirac $\delta$-function (Dirac, 1947, p. 58), e.g., via

$$\frac{1}{r}\int_0^\infty 1(t - r/V)e^{-pt}dt = \frac{1}{pr}\int_0^\infty e^{-pt}d_t 1(t - r/V) \tag{39}$$

$$\text{“}=\text{”} \quad \frac{1}{pr}\int_0^\infty e^{-pt}\delta(t - r/V)dt. \tag{40}$$

Although the “$\delta$-function” has its very useful aspects, I prefer to avoid it because a consistent use of it entails such complicated revisions of integral calculus that the simplicity it introduces is only apparent. It may very well be, however, that a

thoroughgoing $\delta$-function treatment of the problem would be very valuable (Schwartz, 1950).

Using the standard Laplace inversion formula one is led quickly to an analytical expression for the function sought, say $A(p, z; t)$. But this involves a double integral or, if equation (15) or (17) is used, a triple integral. The reduction of this to the relatively simple forms arrived at by Cagniard seems to require the evaluation of the integral of the form shown at the center of equation (14) (which is done at the left side of equation (14) but is not easily carried out in the more interesting cases).

Other lines of attack have also been followed. For example, a very natural way to proceed is to regard equation (19) as a transformation from $\omega$ to $t'$. This gives promise of being the most direct approach. However, to utilize this, one needs a generalization of Dirichlet's double integral inversion formula to cover complex paths of integration. A hasty survey of the literature has not revealed the existence of such a generalization. My attempt to deduce one leads me to conclude tentatively that the easiest way to arrive at this generalization is via Cagniard's process outlined above. So I arrive at the conclusion that Cagniard's procedure is the simplest that I have been able to find.

An expression alternate to equation (34) may be found by closing the path along curves of equation (19) (see Figure 5(b)). Then using Cauchy's theorem we can show that $C_{t'}$ in equation (32) may be replaced by $AF$ (Fig. 5(b)). But $AF$ in the $u$-plane is the map of a real segment in the $t'$-plane between $t$, the time in question, and $r/V$, the least time. So we can transform equation (32) into such a real time integral. I had hoped that this real time integral would permit a closer direct understanding of the physical process but the integrand is complex and complicated and appears not to be useful.

The above skeleton outline gives the main steps in handling all the curl-free contributions in a reflection problem. E.g., in case of the buried source at a depth, $h$, under a free plane surface, we have to replace (Cagniard, 1939, p. 52, equation (39))

$$e^{-pa|z-h|}/a$$

by $-e^{-pa(z+h)}/a$ for the image-reflected portion and by

$$\frac{-2bu^2e^{-pa(z+h)}}{(u^2+1/2v^2)^2-abu^2}$$

(where $v$ is the transverse wave velocity and $b=+(u^2+1/v^2)^{1/2}$) to get the correction term which includes surface wave effects. For the more general case the expressions are more complicated algebraically but the procedure applied to them is the same as that outlined above (Cagniard, 1939, p. 115–117).

In case of the curl contribution, or the transverse wave part, a minor change has to be made (Cagniard, 1939, p. 55, equation (3)) to permit the handling of $J_1(pu\rho)$ instead of $J_0(pu\rho)$. Although the algebraic complexity is much increased, no other change is needed.

So, to recapitulate briefly, the reader will find the formula that Cagniard (1939, p. 39, first formula of section 16) uses without proof derived by Cagniard's own method. Cagniard's method is not to use the standard Laplace transform inversion formula, but to use a series of transformations to beat the expression for the Laplace transform into the explicit Laplace transform integral, thus permitting us to extract the desired solution directly out of this integral expression.

Why does the method of Cagniard appear so attractive—specifically to the present writer? It permits a setting of the seismic reflection and refraction problem that appears to be free of the assumption that steady state solutions exist in the case of sources starting at a particular finite time. That steady state solutions exist is clear from the beginning. That they form a class from which solutions of the pulse problems can be synthesized is not a priori clear to me. But by Cagniard's method this may be established (Cagniard, 1939, Chapter 9).

But why is it so important to be sure of each of these details? Why not just use the steady-state approach and then use the uniqueness theorem (Love, 1934, p. 176–177) to establish that any solution of the equations of motion satisfying the source condition and the interface conditions (which are really part of the equations of motion) is the only possible solution? The method of derivation is not important—it may be full of guesses and even logically wrong. I have not always fully appreciated this point and so I have preferred the strict Cartesian approach. But clearly a greater flexibility is achieved by permitting any method of operation followed by an application of the uniqueness theorem.

An advantage of Cagniard's method which appears to outweigh all others is that it permits exact numerical computation of examples, whereas alternate approaches usually appeal to asymptotic approximations good only at large distances ($\rho$'s). Cagniard's method is simplest at and near $\rho = 0$, which is just the region of maximum interest for reflection prospecting.

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GEOPHYSICS, VOL. XIX, NO. 4 (OCTOBER, 1954), PP. 739–760, 9 FIGS.

# MAPPING NEARLY VERTICAL DISCONTINUITIES BY EARTH RESISTIVITIES*

Ö. LOGN†

## ABSTRACT

Following a procedure similar to the method used by Stefanesco et al. (1930) in resistivity computations for a horizontally bedded earth, integral formulas are evaluated for the potential distribution around one current electrode placed in the neighbourhood of (a) one vertical plane of discontinuity and (b) two vertical planes of discontinuity. The integral formulas are shown to be identical to the series evaluated by Hedström (1932) using a Maxwell theory of images. The apparent resistivity in the one-current-electrode configuration is defined, and integral formulas are given for planes of discontinuity. Because the evaluation of apparent resistivity curves across a gangue of small thickness is troublesome by these formulas, approximation formulas for a thin vertical sheet are evaluated, and these are found to be of sufficient accuracy in most cases met in the field.

It is suggested that nearly vertical faults, rock boundaries, and breccias in many cases give geoelectrical anomalies which can be assumed to be caused by vertical planes of discontinuity. As an example, resistivity data are presented which were taken across a breccia in Meheia, near Kongsberg, Norway.

## INTRODUCTION

The apparent resistivity defined by Wenner (1915) was first applied by Gish and Rooney (1925) to depth determination in a horizontally bedded earth. This method has been extensively applied by civil engineers to determine the depth to bedrock. A great number of publications on this subject appeared in the following ten years. Several of the writers have discussed the disturbing effects of lateral discontinuities in the overburden. Hummel (1932) has computed the effect of a spherical body having a high conductivity, and Tagg (1930) has computed resistivity curves for the Wenner configuration across a vertical fault plane. Hubbert (1932) and others (*e.g.*, Leonardon, 1934) have published fault investigations using the Wenner configuration with constant electrode spacing.

Only a few authors have applied the one-electrode configuration in lateral resistivity work. Hedström (1932) has computed the potential distribution around one current electrode placed in the neighbourhood of one or two vertical discontinuity planes, using the Maxwell method of images. As shown in the present work, the same results can be obtained with a procedure related to the method of Stefanesco et al. (1930) for computing the resistivity in a horizontally layered earth. In the case of two vertical planes of discontinuity, the computation of resistivity curves from the mathematical theory is rather troublesome; this has led to the development of a set of resistivity approximation formulas which are derived herein.

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ONE VERTICAL PLANE OF DISCONTINUITY

An electric current of $I$ amperes, introduced into an earth of resistivity $\rho$ ohm-meters through a point electrode $A$ placed on the surface of the earth and another electrode placed at infinity, will give an electric potential of

$$V = I\rho/2\pi R \tag{1}$$

at a distance $R$ from electrode $A$. The earth is assumed to be homogeneous and isotropic. When the current electrode $A$ is placed at a distance $a$ from a vertical, semi-infinite plane of discontinuity (Figure 1), the normal potential given by

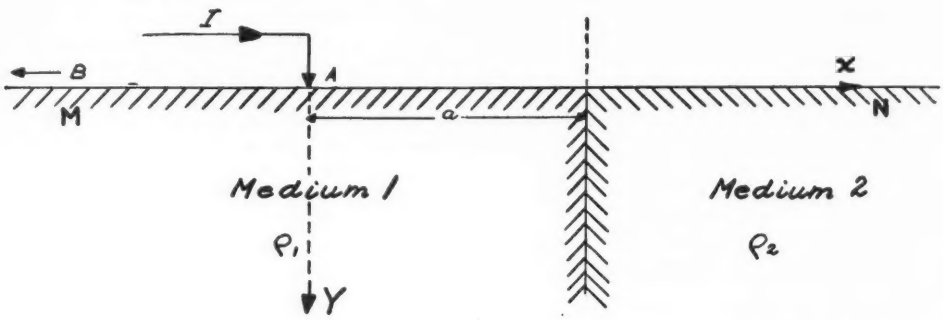


FIG. 1. One-current electrode configuration in the case of one vertical discontinuity plane.

equation (1) will be modified by a secondary potential caused by the presence of medium 2.

A coordinate system is placed with its origin at $A$, positive $x$-axis perpendicular to the boundary plane and to the right, positive $y$-axis downwards, and positive $z$-axis perpendicular to and out of the plane of the paper. As above, the media are assumed to be homogeneous and isotropic, medium 1 having resistivity $\rho_1$ and medium 2 having resistivity $\rho_2$. The formal mathematical solutions must meet the following conditions:

1. They must satisfy Laplace's equation everywhere except at the point $A$.
2. They must approach infinity as $1/R$ at the point $A$, where $R^2=x^2+y^2+z^2$.
3. The potential must vanish at infinity as $1/R$.
4. $V_1=V_2$ and $(1/\rho_1)\partial V_1/\partial x=(1/\rho_2)\partial V_2/\partial x$ at $x=a$.
5. $\partial V_1/\partial y=\partial V_2/\partial y=0$ at $y=0$.

When the problem is considered in cylindrical coordinates in which $r^2=y^2+z^2$ and $\tan\phi=y/z$, condition 5 infers that the solution must be an even function of the angle. Such a solution can be obtained only if one omits from Laplace's equation the term which contains $\phi$. Thus, Laplace's equation in this instance is written as:

$$\frac{\partial^2 V}{\partial r^2}+\frac{1}{r}\frac{\partial V}{\partial r}+\frac{\partial^2 V}{\partial x^2}=0.$$

We now look for a solution in the form of $U(r)e^{\pm\lambda x}$, which yields, when substituted into Laplace's equation,

$$\frac{\partial^2 U}{\partial r^2} + \frac{1}{r}\frac{\partial U}{\partial r} + \lambda^2 U = 0 \tag{2}$$

where $\lambda$ is an undetermined parameter. Equation (2) is the Bessel equation of zero order and has for its solutions the Bessel functions of the first and second kinds, $J_0(\lambda r)$ and $Y_0(\lambda r)$, as well as linear combinations of these functions. Here, the Bessel function of the first kind will be used, so that the solution is:

$$U_\lambda = e^{\pm\lambda x} J_0(\lambda r).$$

Since all linear combinations are also solutions,

$$U = \int_0^\infty \theta(\lambda) e^{-\lambda x} J_0(\lambda r)\, d\lambda + \int_0^\infty \Psi(\lambda) e^{\lambda x} J_0(\lambda r)\, d\lambda \tag{3}$$

where the functions $\theta(\lambda)$ and $\Psi(\lambda)$ have to be determined by means of the boundary conditions.

The potentials in each of the two media are separated into a normal and a secondary potential:

$$V_1 = \frac{I\rho_1}{2\pi}(1/R + V_{s_1}) \quad \text{and} \quad V_2 = \frac{I\rho_1}{2\pi}(1/R + V_{s_2})$$

where $R^2 = x^2 + y^2 + z^2$.

Substituting the integrals (3) into these equations, and putting the fundamental solution of Laplace's equation into the form,

$$1/R = \int_0^\infty e^{-\lambda|x|} J_0(\lambda r)\, d\lambda$$

we get:

$$V_1 = \frac{I\rho_1}{2\pi}\left[\int_0^\infty e^{-\lambda|x|} J_0(\lambda r)\, d\lambda + \int_0^\infty \theta_1(\lambda) e^{-\lambda x} J_0(\lambda r)\, d\lambda + \int_0^\infty \Psi_1(\lambda) e^{\lambda x} J_0(\lambda r)\, d\lambda\right]$$

$$V_2 = \frac{I\rho_1}{2\pi}\left[\int_0^\infty e^{-\lambda x} J_0(\lambda r)\, d\lambda + \int_0^\infty \theta_2(\lambda) e^{-\lambda x} J_0(\lambda r)\, d\lambda + \int_0^\infty \Psi_2(\lambda) e^{\lambda x} J_0(\lambda r)\, d\lambda\right].$$

These equations contain four unknown functions $\theta_1(\lambda)$, $\theta_2(\lambda)$, $\Psi_1(\lambda)$, and $\Psi_2(\lambda)$. The functions have to be determined in such a way that the first four of the conditions mentioned above are satisfied. Thus, the following system of linear equations with the four unknowns is determined:

$$\theta_1(\lambda) \cdots\cdots\cdots\cdots\cdots\cdots = 0$$

$$e^{-\lambda a}\theta_2(\lambda) - \quad e^{\lambda a}\Psi_1(\lambda) \cdots = 0$$

$$\frac{1}{\rho_2} e^{-\lambda a}\theta_2(\lambda) + \frac{1}{\rho_1} e^{\lambda a}\Psi_1(\lambda) \cdots = \left(\frac{1}{\rho_1} - \frac{1}{\rho_2}\right) e^{-\lambda a}$$

$$\Psi_2(\lambda) = 0.$$

By solving these equations, one gets

$$\theta_1(\lambda) = 0 \qquad \Psi_1(\lambda) = \rho_{21} e^{-2\lambda a}$$

$$\theta_2(\lambda) = \rho_{21} \qquad \Psi_2(\lambda) = 0$$

where

$$\rho_{21} = \frac{\rho_2 - \rho_1}{\rho_2 + \rho_1}$$

and is known as the reflection factor.

Hence, the potentials may be expressed by

$$V_1 = \frac{I\rho_1}{2\pi} \int_0^\infty \left[e^{-\lambda|x|} + \rho_{21} e^{-\lambda(2a-x)}\right] J_0(\lambda r) d\lambda$$

$$V_2 = \frac{I\rho_1}{2\pi} (1 + \rho_{21}) \int_0^\infty e^{-\lambda x} J_0(\lambda r) d\lambda.$$

An evaluation of the integrals yields the closed forms:

$$\left.\begin{aligned} V_1 &= \frac{I\rho_1}{2\pi} \left\{\frac{1}{R} + \frac{\rho_{21}}{\left[(2a - x)^2 + y^2 + z^2\right]^{1/2}}\right\} && \text{for} \quad x < a \\ V_2 &= \frac{I\rho_1}{2\pi} \frac{1 + \rho_{21}}{R} && \text{for} \quad x > a \end{aligned}\right\}. \tag{4}$$

Hedström (1932) has shown that the same equations may be found by the direct application of Maxwell's theory of images.

The determination of the potential field is usually made along straight profiles on the surface of the earth by means of two movable potential electrodes with a constant separation. Since the distance between these electrodes can be assumed to be small in comparison with other inter-electrode distances involved, equation (1) gives us the following expression for the rate of change of potential along the $x$-axis:

$$\frac{V_2 - V_1}{x_2 - x_1} = \frac{\Delta V}{\Delta x} = \frac{\partial V}{\partial x} = -\frac{I\rho}{2\pi x^2}.$$

Solving for $\rho$,

$$\rho = \frac{2\pi x^2}{I}\left(-\frac{\partial V}{\partial x}\right), \tag{5}$$

which expression is also used to define the apparent resistivity $\rho_a$ if the medium is inhomogeneous. This apparent resistivity furnishes a representation of the resistivity conditions near the moving electrodes.

The derivatives of the potentials (4) are

$$\frac{\partial V_1}{\partial x} = \frac{I\rho_1}{2\pi}\left[-\frac{1}{x^2} + \frac{\rho_{21}}{(2a-x)^2}\right]$$

$$\frac{\partial V_2}{\partial x} = -\frac{I\rho_1}{2\pi}\,\frac{1+\rho_{21}}{x^2}$$

when $y=z=0$. Substitution of these derivatives into equation (5) gives us

$$\left.\begin{aligned} \rho_{a_1} &= \rho_1\left[1-\rho_{21}\left(\frac{x}{2a-x}\right)^2\right] \quad \text{when} \quad x<a \\ \rho_{a_2} &= \rho_1(1+\rho_{21}) \qquad\qquad\qquad\quad \text{when} \quad x>a \end{aligned}\right\}. \tag{6}$$

Resistivity curves (Fig. 2) for different values of the reflection factor have been evaluated from equations (6). Since the apparent resistivities are dependent on the first power of the factor $\rho_{21}$, a saturation effect occurs as has been shown by Hedström (1932). As an example, it can be mentioned that a resistivity ratio $\rho_2/\rho_1$ of 1/2 gives a maximum apparent resistivity of 1.33 $\rho_1$, which is only slightly less than the 1.82 $\rho_1$ corresponding to a resistivity ratio of 1/10.

## TWO VERTICAL BOUNDARY PLANES

With two vertical planes separating three homogeneous and isotropic media of resistivities $\rho_1$, $\rho_2$, and $\rho_3$ (Fig. 3), the calculations may be carried out in the same manner. In this case, the boundary conditions are identical with those given for the previous problem with the further provision that conditions similar to condition 4 must also apply at the second boundary, which has been introduced here and where $x=a+b$. Similarly, the applicable differential equation is the same as in the previous example and the solution valid here is also that given by equation (3).

As before, the potential in each of the three regions is broken into a normal part and a secondary part, whence the solutions can be written in the form:

$$V_1 = \frac{I\rho_1}{2\pi}\left[\int_0^\infty e^{-\lambda|x|}J_0(\lambda r)d\lambda + \int_0^\infty \theta_1(\lambda)e^{-\lambda x}J_0(\lambda r)d\lambda + \int_0^\infty \Psi_1(\lambda)e^{\lambda x}J_0(\lambda r)d\lambda\right]$$

$$V_2 = \frac{I\rho_1}{2\pi}\left[\int_0^\infty e^{-\lambda x}J_0(\lambda r)d\lambda + \int_0^\infty \theta_2(\lambda)e^{-\lambda x}J_0(\lambda r)d\lambda + \int_0^\infty \Psi_2(\lambda)e^{\lambda x}J_0(\lambda r)d\lambda\right]$$

$$V_3 = \frac{I\rho_1}{2\pi}\left[\int_0^\infty e^{-\lambda x}J_0(\lambda r)d\lambda + \int_0^\infty \theta_3(\lambda)e^{-\lambda x}J_0(\lambda r)d\lambda + \int_0^\infty \Psi_3(\lambda)e^{\lambda x}J_0(\lambda r)d\lambda\right].$$

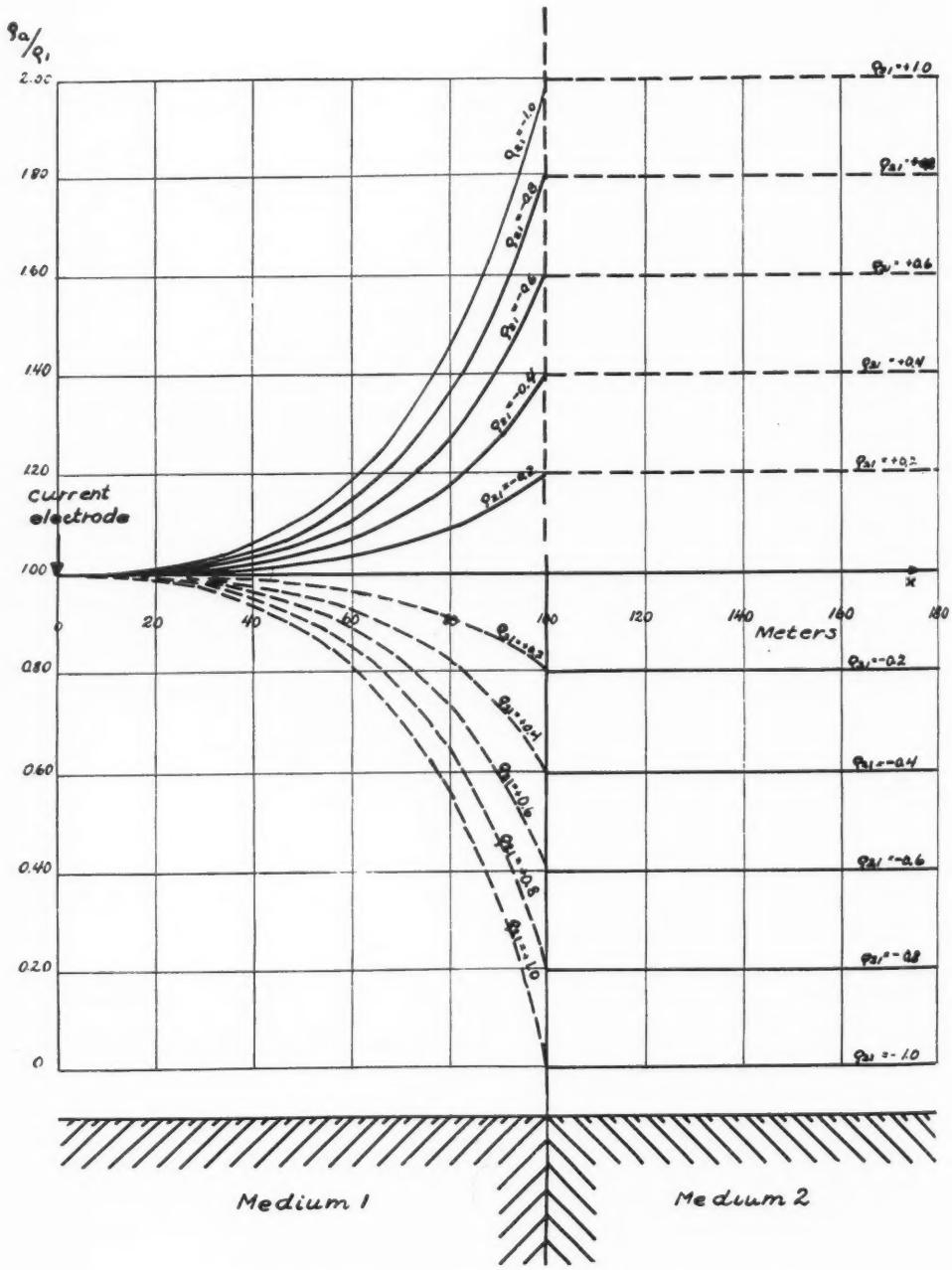


FIG. 2. Apparent resistivity curves across a vertical discontinuity plane ($\rho_2$ variable, $a=100$, $\rho_{21}=\rho_2-\rho_1/\rho_2+\rho_1$).

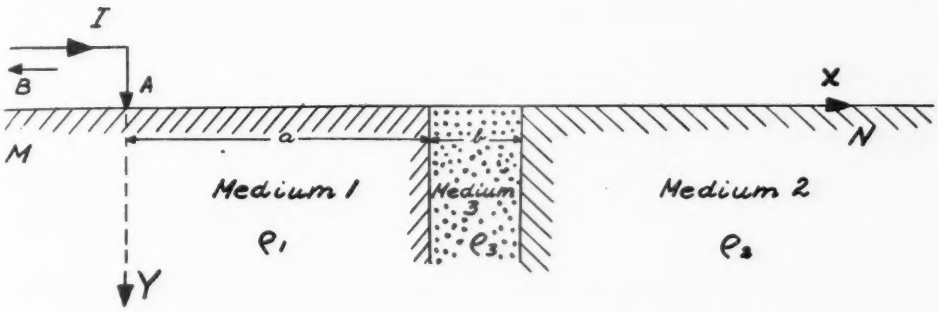


FIG. 3. One current electrode configuration in the case of two vertical discontinuity planes.

These equations contain six arbitrary functions of $\lambda$ which are easily evaluated by the methods outlined in the first example. Therefore, it is found that the potentials are

$$\left.\begin{aligned} V_1 &= \frac{I\rho_1}{2\pi}\int_0^\infty \left[e^{-\lambda x} + \frac{\rho_{31} + \rho_{23}e^{-2\lambda b}}{1 - ke^{-2\lambda b}}\, e^{\lambda(x-2a)}\right] J_0(\lambda r)\,d\lambda \quad \text{for } x < a \\ V_3 &= \frac{I\rho_1}{2\pi}(1 + \rho_{31})\int_0^\infty \frac{e^{-\lambda x} + \rho_{23}e^{\lambda(x-2a-2b)}}{1 - ke^{-2\lambda b}}\, J_0(\lambda r)\,d\lambda \quad \text{for } a < x < a + b \\ V_2 &= \frac{I\rho_1}{2\pi}(1 + \rho_{23})(1 + \rho_{31})\int_0^\infty \frac{e^{-\lambda x}}{1 - ke^{-2\lambda b}}\, J_0(\lambda r)\,d\lambda \quad \text{for } x > a + b \end{aligned}\right\} \quad (7)$$

where

$$\rho_{mn} = \frac{\rho_m - \rho_n}{\rho_m + \rho_n} \quad \text{and} \quad k = \rho_{13}\rho_{23}.$$

Differentiating the equations with respect to $x$, and substituting in the expression for $\rho_a$, we get, at $y=z=0$:

$$\left.\begin{aligned} \rho_{a_1} &= \rho_1 x^2 \int_0^\infty \lambda\left[e^{-\lambda x} - \frac{\rho_{31} + \rho_{23}e^{-2\lambda b}}{1 - ke^{-2\lambda b}}\, e^{\lambda(x-2a)}\right] d\lambda \\ \rho_{a_3} &= \rho_1 x^2(1 + \rho_{31})\int_0^\infty \lambda \frac{e^{-\lambda x} + \rho_{23}e^{\lambda(x-2a-2b)}}{1 - ke^{-2\lambda b}}\, d\lambda \\ \rho_{a_2} &= \rho_1 x^2(1 + \rho_{31})(1 + \rho_{23})\int_0^\infty \lambda \frac{e^{-\lambda x}}{1 - ke^{-2\lambda b}}\, d\lambda\,. \end{aligned}\right\} \quad (8)$$

The integrals can be evaluated graphically but such an evaluation is troublesome, especially when the thickness $b$ of the middle medium is small or when the factors $\rho_{13}$ and $\rho_{23}$ have values close to plus or minus one. However, the integrals may be converted to summations by making use of the expansion,

$$(1 - ke^{-2\lambda b})^{-1} = 1 + ke^{-2kb} + k^2e^{-4\lambda b} + \cdots + k^ne^{-2nkb} + \cdots,$$

which when substituted into the first equation of (8) yields

$$\rho_{a_1} = \rho_1 x^2 \left\{ \int_0^\infty \lambda e^{-\lambda x} d\lambda - \int_0^\infty \lambda [\rho_{31} + (1 - \rho_{13}^2)\rho_{23}(e^{-2\lambda b} + ke^{-4\lambda b} + \cdots + k^{n-1}e^{-2n\lambda b} + \cdots)] e^{\lambda(x-2a)} d\lambda \right\}.$$

Ordinary integration is now possible term by term. In the same manner, we obtain expressions for $\rho_{a_2}$ and $\rho_{a_3}$ so that:

$$\left.\begin{aligned} \rho_{a_1} &= \rho_1 \left[ 1 - \rho_{31} \left( \frac{x}{x - 2a} \right)^2 - (1 - \rho_{13})^2 \rho_{23} \sum_{n=1}^{\infty} k^{n-1} \left( \frac{x}{x - 2a - 2nb} \right)^2 \right] \\ \rho_{a_3} &= \rho_1 (1 + \rho_{31}) \sum_{n=0}^{\infty} k^n \left\{ \left( \frac{x}{x + 2nb} \right)^2 - \rho_{23} \left[ \frac{x}{x - 2a - 2(n+1)b} \right]^2 \right\} \\ \rho_{a_2} &= \rho_1 (1 + \rho_{31})(1 + \rho_{23}) \sum_{n=0}^{\infty} k^n \left( \frac{x}{x + 2nb} \right)^2. \end{aligned}\right\} \quad (9)$$

These series may also be found directly by the use of Maxwell's theory of images (Hedström, 1932).

When $b$ approaches zero in equations (9), the formulas are identical with those in equations (6). Also, when $\rho_3 = \rho_2$, we get

$$\rho_{a_1}' = \rho_1 \left[ 1 - \rho_{31} \left( \frac{x}{2a - x} \right)^2 \right]$$

$$\rho_{a_1}' = \rho_1 (1 + \rho_{31}).$$

When we substitute $\rho_{a_1}'$ and $\rho_{a_2}'$ in equations (9), we obtain

$$\left.\begin{aligned} \rho_{a_1} &= \rho_{a_1}' - \rho_1 (1 - \rho_{13}^2)\rho_{23} \sum_{n=1}^{n=\infty} k^{n-1} \left( \frac{x}{2a - x + 2nb} \right)^2 \qquad \text{for } x < a \\ \rho_{a_2} &= \rho_{a_2}' + \rho_1 (1 + \rho_{31}) \left[ \rho_{23} + (1 + \rho_{23}) \sum_{n=1}^{\infty} k^n \left( \frac{x}{x + 2nb} \right)^2 \right] \text{ for } x > a + b. \end{aligned}\right\} \quad (10)$$

When $b$ approaches infinity, the apparent resistivities are represented by $\rho_{a_1}'$ and $\rho_{a_2}'$. If $\rho_{a_1}$ and $\rho_{a_2}$ are the apparent resistivities on opposite sides of a conducting sheet of thickness $b$, it is seen that $\rho_{a_1}$ will always be smaller than $\rho_{a_1}'$ and $\rho_{a_2}$ will always be greater than $\rho_{a_2}'$ because the second expression in each of equations (10) is positive for a conducting sheet. This fact means that the less conductive medium 2 has to a great extent replaced medium 3, which is a good conductor.

The series in equations (9) converge slowly, especially when $b$ is small, and $k$ has an absolute value close to unity. This difficulty will often be met when one is

prospecting for faults, fissures, etc. In such cases, the evaluation of $\rho_a$ is very troublesome, and it may therefore be desirable to deduce formulas which are more practical for normal operations. This can be done in several ways. In the following discussion, one set of approximation formulas, which has been used by the author, will be derived. It has been found to be sufficiently accurate for use in the field.

Evaluation of the integrals in equations (7) yields:

$$V_1 = \frac{I\rho_1}{2\pi}\left\{\frac{1}{x} + \frac{\rho_{31}}{2a-x} + (1-\rho_{31}^2)\rho_{23}\left[\frac{1}{2a-x+2b} + \frac{k}{2a-x+4b} + \cdots + \frac{k^{n-1}}{2a-x+2nb} + \cdots\right]\right\}$$

$$V_2 = \frac{I\rho_1}{2\pi}(1+\rho_{31})(1+\rho_{23})\left[\frac{1}{x} + \frac{k}{x+2b} + \cdots + \frac{k^n}{x+2nb} + \cdots\right].$$

The potential $V_3$ across the layer in the middle (which we shall assume to be the gangue) is not evaluated, because $b$ is assumed to be so small that the potential electrodes do not touch the gangue.

In the expression for $V_1$, let us add and subtract the term

$$\frac{1-\rho_{13}^2}{\rho_{13}} \cdot \frac{1}{2a-x}$$

on the right side of the equation, obtaining

$$V_1 = \frac{I\rho_1}{2\pi}\left[\frac{1}{x} - \frac{1}{\rho_{13}(2a-x)} + \frac{1-\rho_{13}^2}{\rho_{13}}\sum_{n=0}^{\infty}\frac{k^n}{2a-x+2nb}\right]. \qquad (11)$$

As an approximation, this series may be written as an exponential integral when $b$ is sufficiently small:

$$\sum_{n=0}^{\infty}\frac{k^n}{2a-x+2nb} \approx \int_0^{\infty}\frac{e^{-t\ln(1/k)}dt}{2a-x+2bt} = \frac{1}{2b}\int_0^{\infty}\frac{e^{-t\ln(1/k)}}{\frac{2a-x}{2b}+t}dt. \qquad (12)$$

Let us introduce the exponential integral defined as:

$$-Ei(-y) = \int_{-\infty}^{-y}\frac{e^t dt}{t} = \int_y^{\infty}\frac{e^{-t}dt}{t},$$

tables of which are found in Jahnke and Emde's *Tables of Functions*.

Moreover,

$$\int_y^{\infty}\frac{e^{-mt}dt}{a+t} = -e^{+ma}Ei[-m(a+y)]$$

which, when applied to equation (12), gives us

$$\sum_{n=0}^{\infty} \frac{k^n}{2a - x + 2nb} \approx -\frac{1}{2b} e^{[(2a-x)/2b] \ln (1/k)} Ei\left[-\frac{2a-x}{2b} \ln (1/k)\right].$$

When we introduce this approximation into equation (11), we obtain

$$V_1 \approx \frac{I\rho_1}{2\pi}\left\{\frac{1}{x} - \frac{1}{\rho_{13}(2a-x)} - \frac{1-\rho_{13}^2}{2b\rho_{13}} e^{[(2a-x)/2b] \ln (1/k)} Ei\left[-\frac{2a-x}{2b} \ln (1/k)\right]\right\}.$$

Operating on the expression for $V_2$ in the same manner, we obtain

$$\sum_{n=0}^{\infty} \frac{k^n}{x + 2nb} \approx -\frac{1}{2b} e^{(x/2b) \ln (1/k)} Ei\left[-\frac{x}{2b} \ln 1/k\right]$$

and finally,

$$V_2 = -\frac{I\rho_1}{2\pi b}(1 + \rho_{31})(1 + \rho_{23}) e^{(x/2b) \ln (1/k)} Ei\left[-\frac{x}{2b} \ln 1/k\right].$$

Differentiation with respect to $x$ gives

$$\frac{dV_1}{dx} \approx \frac{I\rho_1}{2\pi}\left\{-\frac{1}{x^2} - \frac{1}{\rho_{13}(2a-x)^2} - \frac{1-\rho_{13}^2}{\rho_{13}}\left[-\frac{1}{4b^2} e^{[(2a-x)/2b] \ln (1/k)} (\ln 1/k) Ei\left(-\frac{2a-x}{2b} \ln 1/k\right) - \frac{1}{2b(2a-x)}\right]\right\}$$

which when substituted into the defining equation for the apparent resistivity produces the desired approximation:

$$\rho_{a_1} \approx \rho_1\left[1 + \frac{1}{\rho_{13}}\left(\frac{x}{2a-x}\right)^2 + \frac{4\rho_1\rho_3}{\rho_1^2 - \rho_3^2} \frac{x}{2b}\left(\frac{x}{2a-x} + u_1 \ln 1/k\right)\right] \quad (13)$$

where

$$u_1 = \frac{x}{2b} e^{[(2a-x)/2b] \ln (1/k)} Ei\left(-\frac{2a-x}{2b} \ln 1/k\right).$$

In the same manner, we obtain

$$\rho_{a_2} \approx \rho_1(1 + \rho_{21})(1 - k) \frac{x}{2b}(1 + u_2 \ln 1/k) \quad (14)$$

where $(1+\rho_{31})(1+\rho_{23})=(1+\rho_{21})(1-k)$ and

$$u_2 = \frac{x}{2b}\, e^{(x/2b)\,\ln 1/k} Ei\left(-\frac{x}{2b}\ln 1/k\right).$$

If $\rho_2$ and $\rho_1$ are very large compared to $\rho_3$, we can make the approximation:

$$k = \rho_{13}\rho_{23} = \left(\frac{\rho_1-\rho_3}{\rho_1+\rho_3}\right)\left(\frac{\rho_2-\rho_3}{\rho_2+\rho_3}\right) = \left(1-\frac{2\rho_3}{\rho_1+\rho_3}\right)\left(1-\frac{2\rho_3}{\rho_2+\rho_3}\right)$$

$$k \approx \left(1-\frac{2\rho_3}{\rho_1}\right)\left(1-\frac{2\rho_3}{\rho_2}\right) \approx 1-2\rho_3\left(\frac{1}{\rho_1}+\frac{1}{\rho_2}\right) = 1-\frac{2\rho_3}{\rho}$$

where

$$\frac{1}{\rho} = \frac{1}{\rho_1}+\frac{1}{\rho_2},$$

which is the sum of the conductivities in the two media.

It then follows that

$$1/k \approx 1 + 2\rho_3/\rho \quad \text{and} \quad 1-k \approx 2\rho_3/\rho.$$

When $x$ is very small, $\ln(1+x)\approx x$ so that $\ln 1/k \approx 2\rho_3/\rho$. Furthermore, we can set $\rho_{13}\approx 1$ and $(4\rho_1\rho_3)/(\rho_1^2-\rho_3^2)\approx 4\rho_3/\rho_1$. Introducing these approximations into equations (13) and (14), we get

$$\begin{aligned}
\rho_{a_1} &\approx \rho_1\left[1+\left(\frac{x}{2a-x}\right)^2 - 2\,\frac{\rho_3}{\rho_1}\,\frac{x}{2b}\left(\frac{x}{2a-x}+2\,\frac{\rho_3}{\rho}\,u_1\right)\right] \\
\rho_{a_2} &\approx \rho_1(1+\rho_{21})\,\frac{\rho_3}{\rho}\,\frac{x}{b}\left(1+2\,\frac{\rho_3}{\rho}\,u_2\right).
\end{aligned} \tag{15}$$

Equation (7) may be written, for the case when $\rho_{21}=-1$,

$$\rho_{a_1}{}^0 = \rho_1\left[1+\left(\frac{x}{2a-x}\right)^2\right].$$

This apparent resistivity has been labelled with the superscript "o" to distinguish it from the others and it is substituted into equation (15):

$$\rho_{a_1} \approx \rho_{a_1}{}^0 - 2\,\frac{\rho_3}{\rho_1}\,\frac{x}{2b}\left(\frac{x}{2a-x}+2\,\frac{\rho_3}{\rho}\,u_1\right).$$

Substituting the expressions

$$2a_1 = 2\,\frac{\rho_3}{\rho}\,\frac{a}{b}, \quad z = \frac{\rho_3}{\rho}\,\frac{x}{b}, \quad \text{and} \quad z_1 = \frac{\rho_3}{\rho_1}\,\frac{x}{b}$$

we obtain:

$$\left.\begin{aligned}\rho_{a_1} &\approx \rho_{a_1}{}^0 - 2z_1\rho_1\left\{\frac{z}{2a_1 - z} + ze^{2a_1 - z}Ei[-(2a_1 - z)]\right\}\\ \rho_{a_2} &\approx \rho_1(1 + \rho_{21})z[1 + ze^{z}Ei(-z)].\end{aligned}\right\}. \tag{16}$$

Similar calculations are to be carried out for the case of a vertical insulating sheet in which we assume that $\rho_3 \gg \rho_1$ and $\rho_3 \gg \rho_2$. We have

$$k = \left(-1 + \frac{2\rho_2}{\rho_2 + \rho_3}\right)\left(-1 + \frac{2\rho_2}{\rho_2 + \rho_3}\right) \approx \left(-1 + \frac{2\rho_1}{\rho_3}\right)\left(-1 + \frac{2\rho_2}{\rho_3}\right)$$

$$k \approx 1 - 2(\rho_1 + \rho_2)/\rho_3 = 1 - 2\Omega/\rho_3$$

where $\Omega = \rho_1 + \rho_2$ or the sum of the resistivities of the two media.

We may also write the approximations $\ln 1/k \approx 2\Omega/\rho_3$, $1 - k \approx 2\Omega/\rho_3$, and $(4\rho_1\rho_3)/(\rho_1{}^2 - \rho_3{}^2) \approx -4\rho_1/\rho_3$, which when introduced into equation (13) give

$$\rho_{a_1} \approx \rho_1\left\{1 - \left(\frac{z}{2a_1 - z}\right) + 2z_1\left[\frac{z}{2a_1 - z} + ze^{2a_1 - z}Ei(-[2a_1 - z])\right]\right\}$$

where

$$z = \frac{\Omega}{\rho_3}\frac{x}{b}, \quad a_1 = \frac{\Omega}{\rho_3}\frac{a}{b}, \quad \text{and} \quad z_1 = \frac{\rho_1}{\rho_3}\frac{x}{b}.$$

When $\rho_{21} = +1$, equation (7) becomes

$$\rho_{a_1}{}^{\infty} = \rho_1\left[1 - \left(\frac{x}{2a - x}\right)^2\right].$$

Whence we can write:

$$\left.\begin{aligned}\rho_{a_1} &\approx \rho_{a_1}{}^{\infty} + 2z_1\rho_1\left\{\frac{z}{2a_1 - z} + ze^{2a_1 - z}Ei[-(2a_1 - z)]\right\}\\ \rho_{a_2} &\approx \rho_1(1 + \rho_{21})z[1 + ze^{z}Ei(-z)]\end{aligned}\right\}. \tag{17}$$

By means of available tables of $e^z$ and $Ei(-z)$, the resistivities $\rho_{a_1}$ and $\rho_{a_2}$ can be evaluated by use of formulas (16) and (17) with sufficient accuracy when $b$ is small. $\rho_{a_1}{}^0$ and $\rho_{a_1}{}^{\infty}$ are the apparent resistivities of the medium in which the current electrode is located when this medium is in contact along a vertical plane with a very good conductor and a good insulator of infinite thickness, respectively. $\rho_{a_1}{}^0$ and $\rho_{a_1}{}^{\infty}$ can be evaluated for all electrode distances independently of the factors $\rho_2$, $\rho_3$, and $b$. Since $\rho_{a_1}{}^{\infty}$ differs from $\rho_{a_1}{}^0$ only in the sign of a correction term added to $\rho_1$, there must exist a set of resistivity values $1/\rho_1$, $1/\rho_3$, and $1/\rho_2$ for an "insulating sheet" which yields a curve for its $\rho_{a_1}$ which varies in the same way as the corresponding curve for a "conducting sheet" involving resistivities $\rho_1$, $\rho_3$, and

$\rho_2$. Further, it is noticed that $\rho_{a_2}$ has the same values for the same electrode distances in these two cases. Thus, the resistivity curve across an insulating vertical sheet can be evaluated directly from the resistivity across the corresponding conducting sheet.

According to the approximation formulas of equation (17), $\rho_{a_1}$ and $\rho_{a_2}$ depend on the factors $z$, $a_1$, and $z_1$, defined as follows:
For a thin conducting sheet,

$$z = \frac{\rho_3}{\rho}\cdot\frac{x}{b}, \quad a_1 = \frac{\rho_3}{\rho}\cdot\frac{a}{b}, \quad \text{and} \quad z_1 = \frac{\rho_3}{\rho_1}\cdot\frac{x}{b}.$$

For a thin insulating sheet,

$$z = \frac{\Omega}{\rho_3}\cdot\frac{x}{b}, \quad a_1 = \frac{\Omega}{\rho_3}\cdot\frac{a}{b}, \quad \text{and} \quad z_1 = \frac{\rho_1}{\rho_3}\cdot\frac{x}{b}.$$

The resistivities $\rho_1$ and $\rho_2$, and the electrode distance $a$ are supposed to be constant. Then the resistivity in the case of a conducting sheet is dependent on the factor $\rho_3/b = 1/(c\cdot b)$, where $c$ is the conductivity of the sheet, and in the case of an insulating sheet, it depends on the factor $1/(\rho_3\cdot b)$. *The apparent resistivity across a conducting sheet will therefore be determined by the product of the conductivity and the thickness of the sheet, and the apparent resistivity across an insulating sheet is determined by the product of the resistivity and the thickness of the sheet.*

Figures 4, 5, and 6 show curves of $\rho_a/\rho_1$ in the two media evaluated for different resistivity ratios. In Figures 4 and 5, $\rho_2$ is varying, while the other factors are held constant. In Figure 4, the resistivity ratio of the media 1 and 3 is small (10:1); in Figure 5 the resistivity ratio is great (1,000:1). In Figure 6 the thickness varies, and the resistivities are held constant.

The curves are discontinuous. Owing to the very small thickness of the vertical sheet, the true relationships do not show up in the curves as drawn. The apparent resistivities across medium 3 are in all evaluated cases nearly zero, and the resistivity curves have two points of discontinuity, one at $x=a$, and the other at $x=a+b$. Generally the sheet and the rocks are covered by an overburden. If this overburden has a resistivity of the same order of magnitude as the rocks, it has only a small influence on the current distribution, and gives rise to small differences in the resistivity curves. Laboratory measurements made on model sheets with their upper limits at a certain depth below the surface have shown that in these cases the resistivity curves are continuous curves with a maximum nearly coincident with the front of the sheet, and a more indistinct minimum behind the sheet.

Figure 4 shows a saturation effect similar to that in the two-sheet problem, where the anomalies are not proportional to the resistivity variations.

Figure 6 shows a similar saturation effect with respect to variation in the thickness of the sheet; the anomalies here are not proportional to the thickness

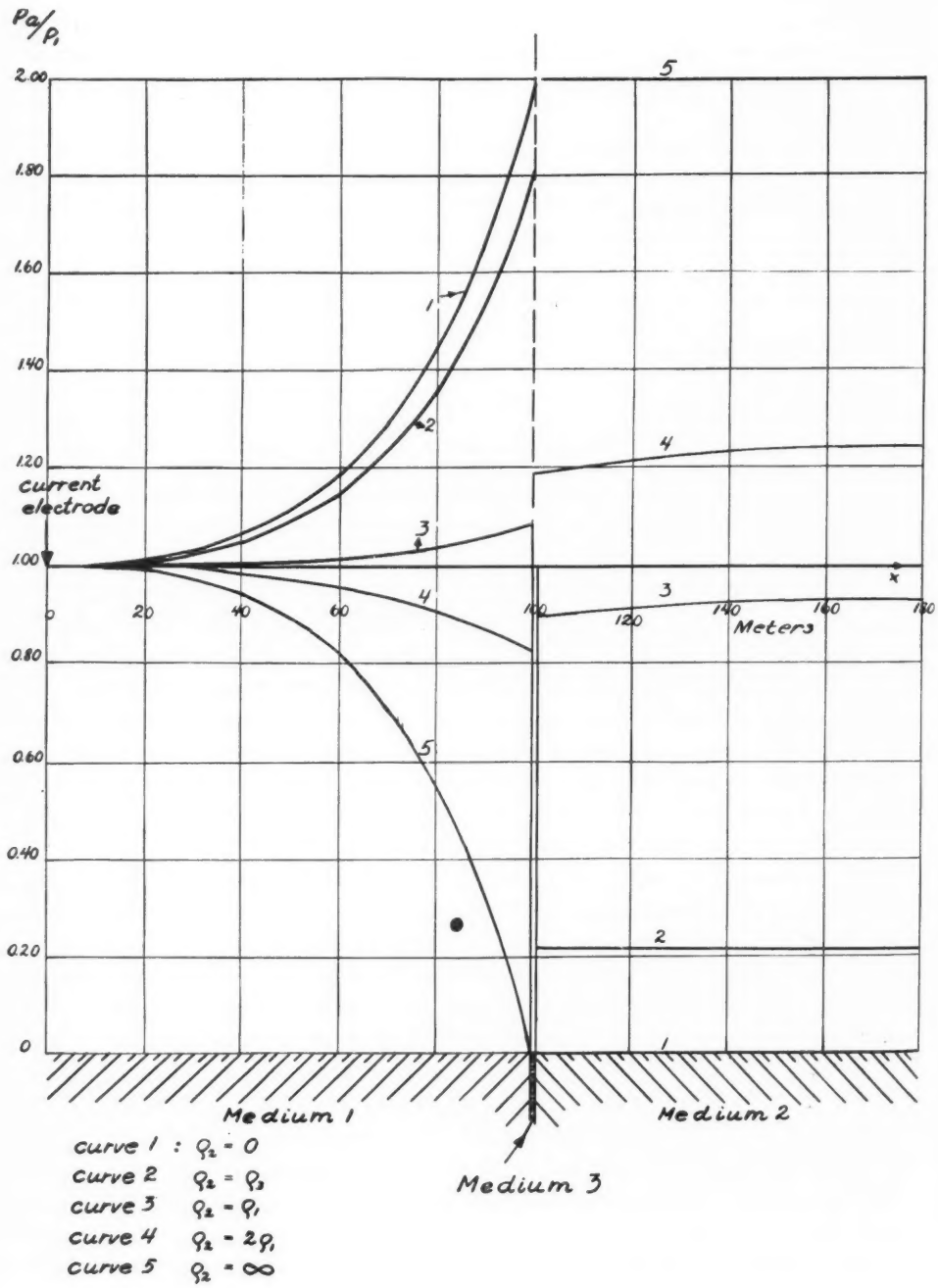


FIG. 4. Apparent resistivity curves across a vertical sheet of thickness $b=1$ ($\rho_2$ variable, $\rho_1/\rho_3=10$, $a=100$).

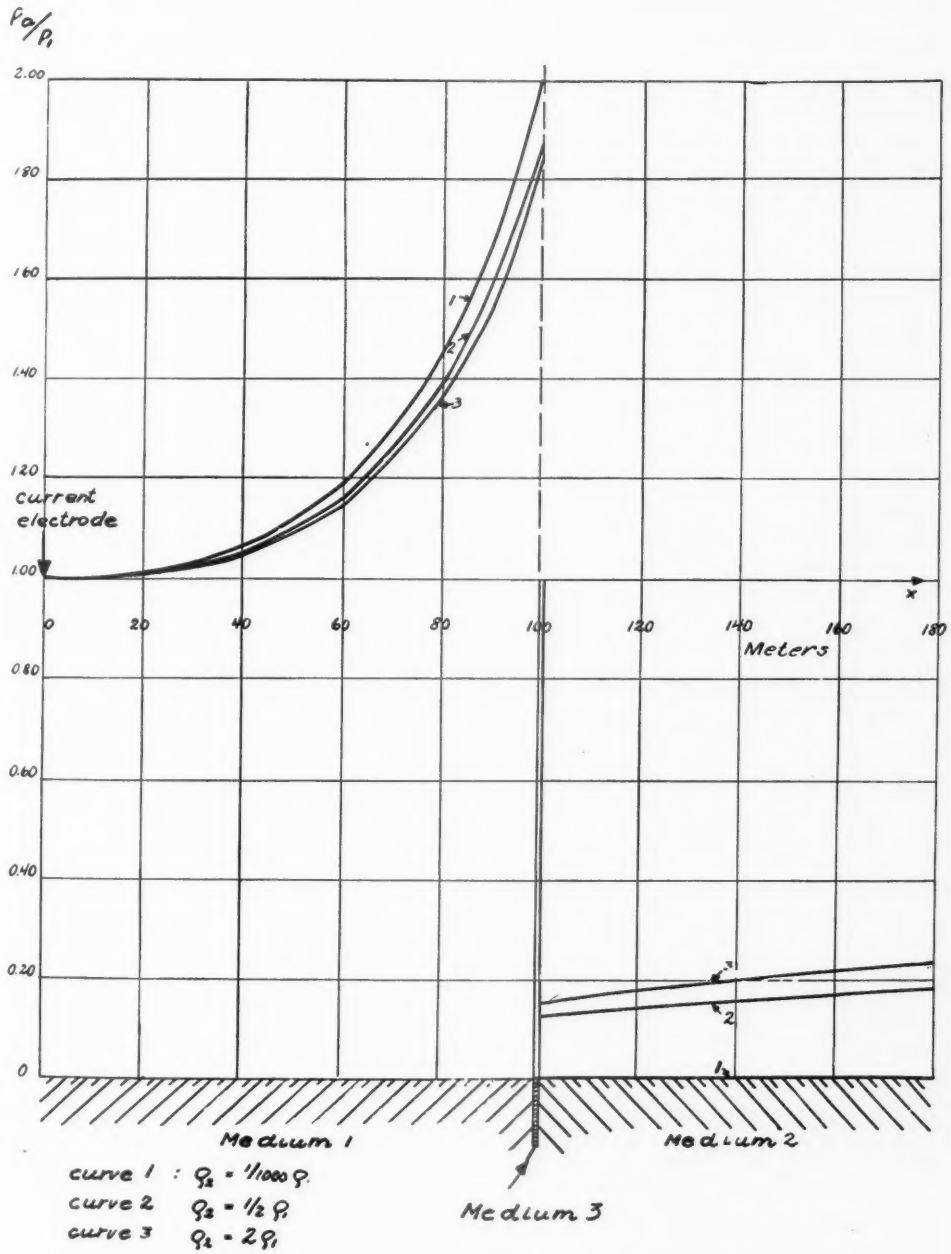


FIG. 5. Apparent resistivity curves across a vertical sheet of thickness $b=1$ ($\rho_2$ variable, $\rho_1/\rho_3=1000$, $a=100$).

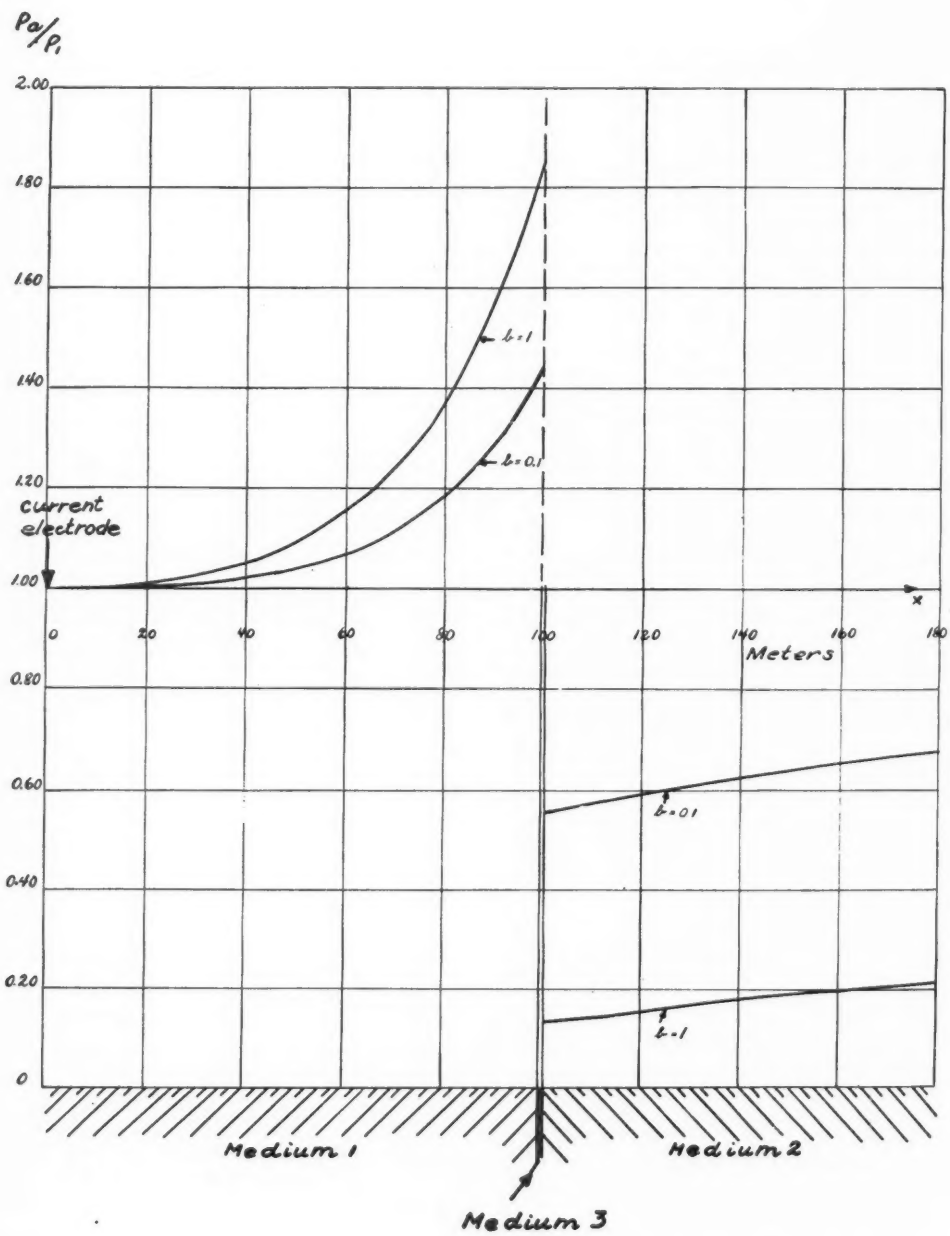


FIG. 6. Apparent resistivity curves across a vertical conducting sheet (thickness $b$ variable, $\rho_1/\rho_3 = 1000$, $\rho_1 = \rho_2$, $a = 100$).

of the sheet. In other words, we have a *resistivity* saturation effect and a *thickness* saturation effect. In this way the method will be very sensitive in the presence of small resistivity differences and of small thicknesses.

Figure 7 shows the resistivity curve across a thin vertical insulating sheet for two values of the thickness. This curve really has two discontinuity points, but these do not appear in the figure. The apparent resistivity in the insulating sheet is high, almost reaching the value $2\rho_1$.

## LATERAL RESISTIVITY DIFFERENCES CAUSED BY GEOLOGY

Resistivity measurements of rocks are greatly dependent on the following four factors:

1. The pore volume of the rock.
2. The form and arrangement of the pores.
3. The resistivity of the water filling the pores.
4. The extent to which the pores are filled by water.

In temperate climates it can be supposed that the pores are completely filled by water, because the layer al ove the water table in which the pores are not completely filled is small in thickness. Measurements (Sundberg, 1932; Jakosky and Hopper, 1937) have shown that the resistivity of the circulating water greatly influences the resistivity of the rocks, whereas the pore volume and the pore arrangement are of subordinate importance. The resistivity of the circulating water is dependent on chemical composition and quantity of dissolved matter. The chemical composition of the water depends on the composition of the surrounding rocks and on the velocity of the circulating water. Under the same circumstances water with a faster rate of circulation would dissolve less rock material than more slowly circulating water. The velocity of the water circulation depends on the pore volume of the rock, but it may in many instances be influenced by the pore volume of the subjacent or surrounding rock. In formations lying above a very massive rock layer, the water will circulate slowly and will thus have a longer time to dissolve rock material. For this reason, the resistivity of rocks may vary between great limits.

### *Nearly Vertical Rock Contacts and Dikes*

Two rocks may under certain circumstances make contact along a sharp, nearly vertical plane of discontinuity. If the circulating water in the two rocks has different resistivities, the contact may be traced by resistivity methods. An igneous rock will usually be enclosed by a border zone of greater or lesser thickness, which may have different physical properties. If the circulating water in this zone has a resistivity different from the resistivity of the water in the igneous material, the border zone can be traced by resistivity measurements on the surface.

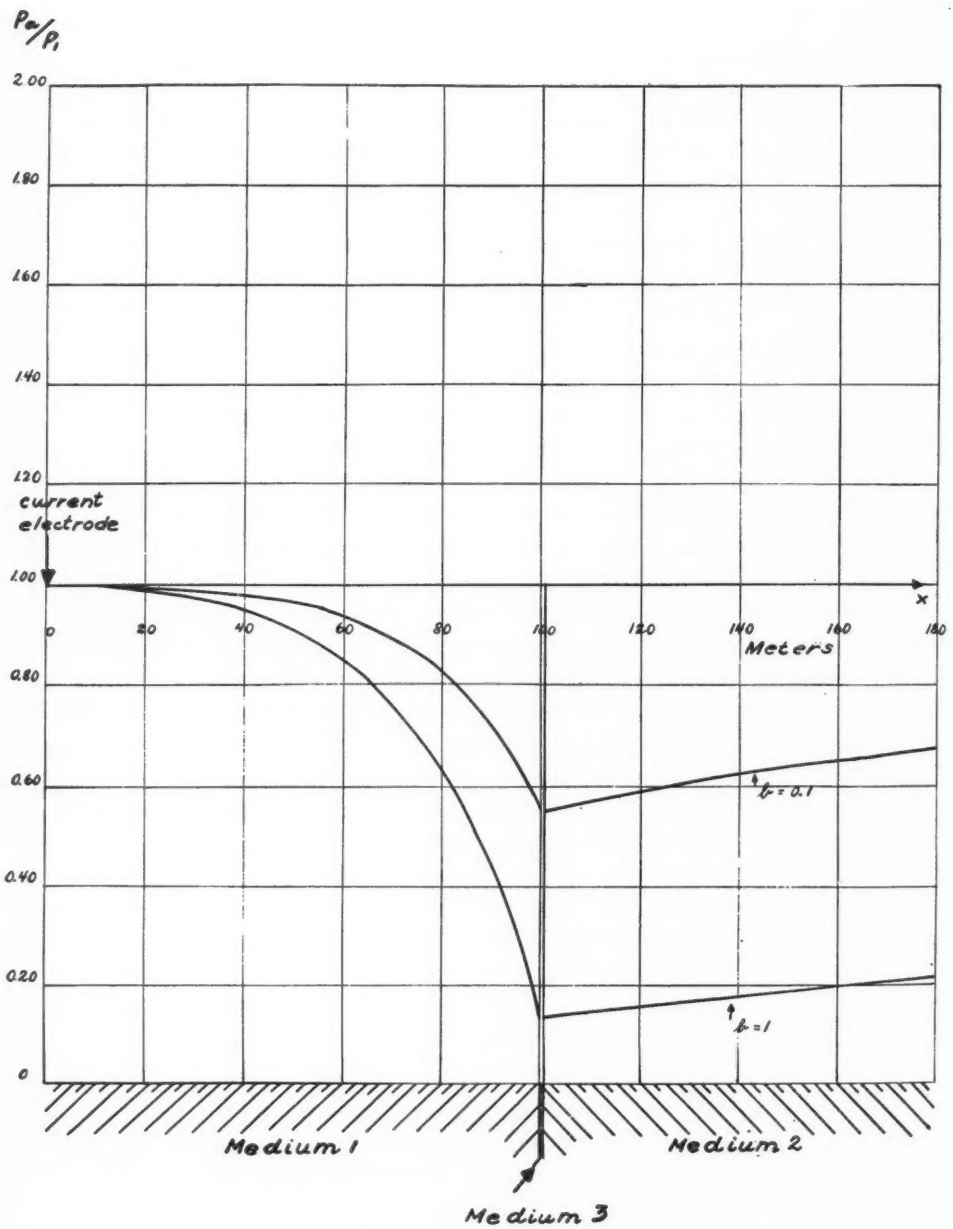


FIG. 7. Apparent resistivity curves across a vertical insulating sheet (thickness $b$ variable, $\rho_1/\rho_2 = 1/1000$, $\rho_1 = \rho_2$, $a = 100$).

*Nearly Vertical Faults*

A fault may or may not have the same rocks on both sides. If the fault cuts like a sharp discontinuity through a uniform rock massive, the fault can not be traced by means of resistivity methods. However, in most cases the fault would appear as a zone of cracked rocks, fissures, shear, etc. This zone may have different physical properties than the original rock itself, and, if the resistivity difference is great enough, the fault zone can be traced out by resistivity measurements on the surface.

*Breccias Having Nearly Vertical Boundaries*

The cracked rocks in a breccia may allow faster circulation of rock waters, which will give the breccia a resistivity which is different from the resistivity of the surrounding rocks. Resistivity methods can therefore be used to trace the breccia. Near the boundaries of the breccia there may exist a thinner zone of greater cracking, which has a resistivity different from the remaining part of the breccia. In this case the breccia boundaries can be traced by resistivity methods which do not require one to know the magnitude of the resistivity of the breccia itself.

The rocks occurring in nature are not homogeneous. However, results obtained with geoelectric methods have shown that as a broad approximation different rocks can be considered as homogeneous with regard to electrical properties. Moreover, the rocks can be considered as isotropic if the most slaty rocks are excluded.

It is seen that the cases above can be represented by the following situations, both of which have been treated mathematically in this paper:

1. One vertical discontinuity plane between two homogeneous and isotropic media of different resistivities.

2. Two vertical discontinuity planes between three, or, in the limit, two, homogeneous and isotropic media of different resistivities.

## PRACTICAL APPLICATION

These theoretical studies were made in conjunction with some geoelectric investigations in Meheia near Kongsberg in Norway. Here a great breccia zone separates the following two pre-Cambrian formations: the western, younger Telemark formation, and the eastern, older Kongsberg-Bamle formation. Both formations are built up of granites and gneisses.

Figures 8 and 9 show resistivity curves along profiles across this breccia. The apparent resistivity is drawn to an arbitrary scale, and the distance along the profile is reckoned from an arbitrary point lying about a hundred meters from the western contact. In Figure 8, resistivity curves at three different electrode locations are drawn, whereas Figure 9 shows resistivity curves at two electrode locations. The curves show that the breccia can be well delineated by means of resis-

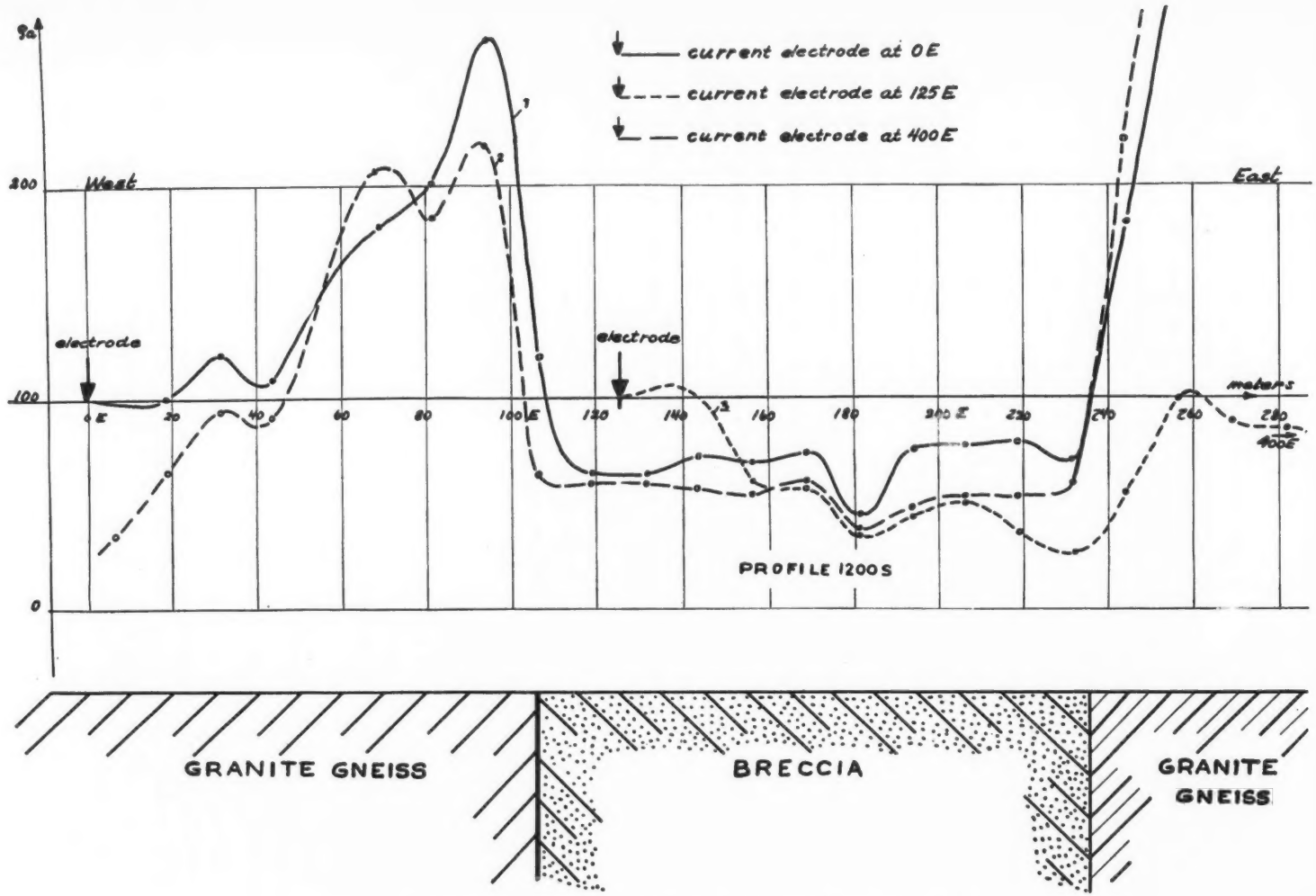


FIG. 8. Resistivity curves across a breccia in Meheia near Kongsberg, Norway.

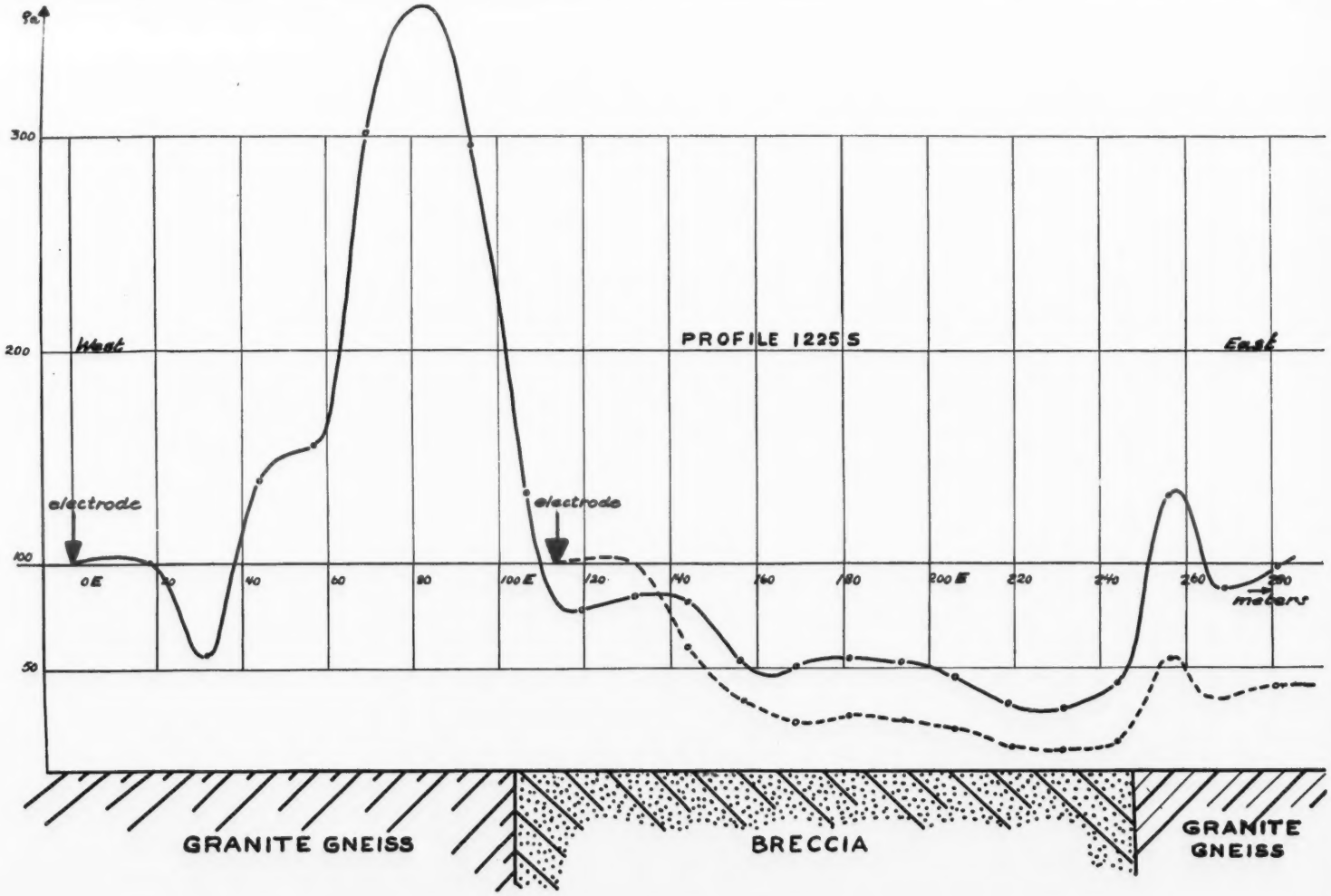


FIG. 9. Resistivity curves along another profile across the same breccia in Meheia near Kongsberg, Norway. Each curve corresponds to a different electrode location.

tivity measurements. The breccia has considerably smaller resistivity than the gneisses of the two formations. The curve marked 1 of Figure 8 shows an ascending tendency beyond the discontinuity at 105 meters, and this was thought to indicate a smaller resistivity in a thinner sheet along the contact (compare with Figure 5). An electromagnetic survey made on the same prospect indicated the existence of weak electric conductors at some points along the contact.

In this way the geoelectric investigation was used to help the geologists in tracing the boundaries of the breccia, especially where this boundary was covered by an overburden. At the same time, the geoelectric method gave information on the resistivity of the different parts of the breccia.

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[1] This reference appeared after Mr. Logan's paper was submitted, but it is cited here because of its applicability to the paper.—*The Editor*

GEOPHYSICS, VOL. XIX, NO. 4 (OCTOBER, 1954), PP. 761–70, 11 FIGS.

# INTERPRETATION OF RESISTIVITY DATA OVER FILLED SINKS*

KENNETH L. COOK† AND ROBERT G. VAN NOSTRAND‡

## ABSTRACT

Solutions of Laplace's equation in prolate and oblate spheroidal coordinates are applied to problems that arise in resistivity surveys over filled hemispheroidal sinks. Comprehensive sets of theoretical curves are presented for both horizontal and vertical profiles in the vicinity of filled sinks. The effectiveness of these theoretical curves is demonstrated not only for the interpretation of resistivity data but also for the planning of proper field techniques in resistivity surveying over such sinks. Excellent correlation between theoretical and observed field resistivity curves is shown over a shale sink in the Tri-State lead-zinc mining district, near Joplin, Missouri. It is shown that a filled sink can be approximated in its resistivity edge effects by 1) a vertical dike if the width of the sink is small in comparison with its length and its depth; and 2) a verical fault if the sink is large in comparison with the electrode separation. A study of the Lee and Wenner configurations indicates that the former gives additional information that more than justifies the extra time and expense involved.

## INTRODUCTION

In mining geophysics, an understanding of the apparent resistivity over filled sinks is of considerable usefulness. As an example, in the Tri-State zinc and lead mining district, ore bodies and mineralized zones are associated with filled sinks, which are locally designated "shale sinks" (Lyden, 1950, p. 1254). Under suitable conditions of resistivity contrast, filled sinks lying at shallow depths can be found by resistivity methods, as was shown in the Tri-State district as early as 1929 (Maillet and Migaux, 1942, p. 73–75; Jakosky et al., 1942).

During the past twenty years, many theoretical papers on quantitative interpretation of resistivity data have been published. Most of these papers deal with either horizontal or vertical plane discontinuities (Tagg, 1930; Hummel, 1932; Roman, 1933 and 1951; and others). Mathematical solutions of the apparent resistivity over certain curved boundary surfaces have been published by Tikhonov (1942), Lipskaya (1949), Seigel (1952), Van Nostrand (1953), and others. However, we know of no treatment for the ellipsoidal and hemispherical sink problems.

The objectives of the present paper are (1) to summarize the theoretical treatment used in solving the ellipsoidal and hemispherical sink problems, (2) to show how the theoretical results can be used to interpret field data obtained with the Lee and Wenner configurations, and (3) to devise field techniques to discover and outline filled sinks in regions where they are believed to exist. Although the data

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and curves shown are specific, the conclusions are believed to have general utility.

The subject matter has been organized to allow readers who are interested only in the practical phase of this problem to omit the section on "Outline of the Theory" without losing the continuity of the discussion.

## OUTLINE OF THE THEORY

### *Ellipsoidal, Spheroidal, and Hemispherical Boundaries*

In solving problems in potential theory that arise in the interpretation of resistivity data, it is often convenient to choose a coordinate system in which a selected boundary can be represented by a constant value of one of the coordinates. The potential functions are then determined so that the potential at each potential electrode due to each current electrode can be calculated. Finally, the potential differences between pairs of potential electrodes due to a given current flowing between a pair of current electrodes are obtained and converted into apparent resistivity values.

In the present problem, most filled sinks can be approximated by ellipsoids. The most general case is an ellipsoid whose three axes are of different lengths. However, the solution of Laplace's equation in ellipsoidal coordinates is made difficult by the comparatively small amount of information that has been published concerning the Lamé functions involved in the solution. Because of this mathematical difficulty, no attempt has been made to solve the most general case.

Ellipsoids of revolution, called spheroids, lead to a solution of the filled-sink problem, which is amenable to a practical mathematical treatment. Numerical tables are available (Lowan, 1945) so that the formal mathematics can readily be converted into useful curves.

Two coordinate systems available for this study are prolate and oblate spheroidal coordinates (Fig. 1) (Smythe, 1950, p. 158–169). A prolate spheroidal coordinate system comprises the three orthogonal families of surfaces: prolate spheroids, hyperboloids of two sheets, and planes intersecting in the $z$-axis. The common foci of all the hyperboloids, which coincide with the common foci of all of the ellipsoids, lie at the points $z=+b$ and $z=-b$. The parameter of the spheroids, $\eta$, varies from 1 to $\infty$. For $\eta=1$, the spheroid is degenerate and consists of the segment of line connecting the points $z=+b$ and $z=-b$. For large values of $\eta$, the spheroids approach a spherical shape. The parameter of the hyperboloids, $\xi$, varies from $-1$ to $+1$. The portion of the $z$-axis for $z>b$ coincides with $\xi=1$ and that for $z<-b$ coincides with $\xi=-1$. The surface for $\xi=0$ corresponds to the $xy$-plane in rectangular coordinates. The complete prolate coordinate system is obtained by rotating about the $z$-axis the diagram in Figure 1e. Therefore, the third variable is the angle $\phi$ which is identical to the corresponding angle in cylindrical coordinates.

The prolate spheroidal coordinate system, with the $z$-axis oriented vertically,

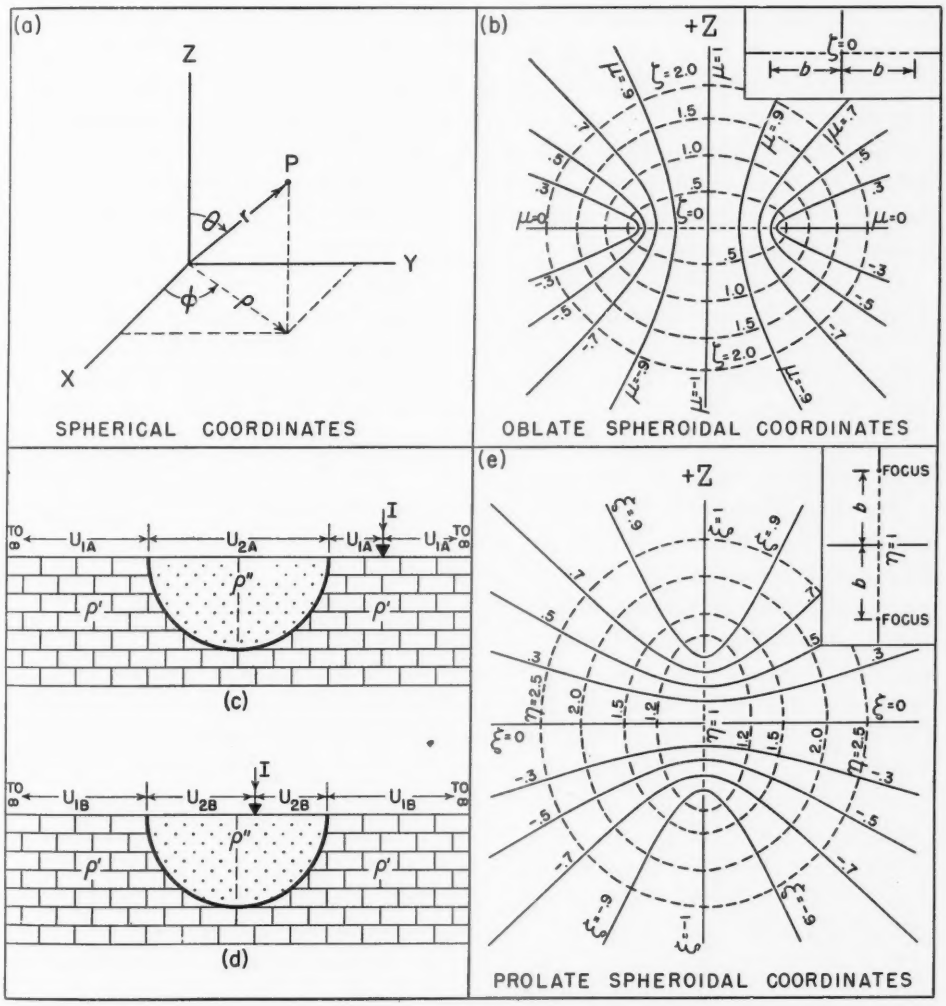


FIG. 1. Coordinate systems, notations, and conventions used in resistivity theory for filled sinks. (a) Spherical coordinates; (b) oblate spheroidal coordinates; (c) cross section of sink with current source outside of sink; (d) same with current source inside of sink; (e) prolate spheroidal coordinates. Surfaces of constant third dimension in (b) and (e) are azimuthal planes through the vertical $z$-axis.

can be used to investigate a sink that is circular in plan view and has a depth greater than the radius of this circle. The same coordinate system, with the $z$-axis oriented horizontally, can be used to approximate a sink that is elliptical in plan view and approximately circular in cross-section perpendicular to its major axis.

Oblate spheroidal coordinates are formed by the families of orthogonal surfaces that are oblate spheroids, hyperboloids of one sheet, and planes intersecting in the $z$-axis. The spheroidal parameter, $\zeta$, varies from 0 to $\infty$. Instead of a pair of

foci, as in the previous case, a focal circle of radius $b$ lies in the $xy$-plane. The points for which $\zeta=0$ also lie in the $xy$-plane within the focal circle. For large values of $\zeta$, the spheroids approach spheres as before. The parameter of the hyperboloids, $\mu$, varies from $-1$ to $+1$. Points for which $\mu=-1$ lie on the negative $z$-axis, and points for which $\mu=1$ lie on the positive $z$-axis. For the entire $xy$-plane outside of the focal circle, $\mu=0$. As in the prolate spheroidal case, the entire system of oblate spheroidal coordinates can be obtained by rotating about the $z$-axis the diagram in Figure 1b.

In a specific geologic application, $\zeta$ is so chosen that it approximates the boundary surface of the filled sink. The oblate spheroidal coordinate system, with the $z$-axis oriented vertically, can be used to approximate a filled sink that is circular in plan and has a depth less than the radius of this circle. The same coordinate system, with the $z$-axis oriented horizontally, can be used to approximate a sink that is elliptical in plan view and approximately circular in a cross section taken perpendicular to its minor axis.

In employing either of the above coordinate systems—and in general—one customarily designates a given plane as the surface of the earth. Usually the plane so chosen must be a plane of symmetry.

From the mathematical and physical standpoints, the basic problem in obtaining theoretical resistivity curves is to derive a formula for the potential due to a point source of current in the vicinity of the boundary (or boundaries) between materials of different resistivities. Since two current electrodes are always necessary in an electrical survey,[1] the total potential at a point is obtained by superposition of the potentials due to the two current electrodes taken separately. It can be shown that the potential functions which arise as the solution of this problem satisfy Laplace's equation. In this paper, only the working formulas, which evolve in the solution of Laplace's equation, will be given.

Consider a spheroidal sink (Fig. 1c) whose boundary is given by $\eta=\eta_1$ in prolate spheroidal coordinates. Let the resistivity of the material within the sink be $\rho''$ and that of the country rock be $\rho'$. Four distinct expressions for the potential functions must be derived according to whether the current source and the field point at which the potential is desired are separately within the sink or in the country rock: two expressions are for the case in which the current source lies outside the sink and two for the case in which the current source lies inside. In each case, the pair of potential functions is such that the necessary boundary conditions are satisfied; that is, the potential and the normal component of the current density must be continuous across the boundary.

On the potential function $U$, the subscript $A$ indicates that the current source lies in the region of resistivity $\rho'$ (Fig. 1c); the subscript $B$ indicates that the current source is located in the region of resistivity $\rho''$ (Fig. 1d), that is, within the sink; the subscript 1 labels the potential outside the sink, and the subscript 2

[1] One of these two electrodes is placed at infinity for some configurations.

is used for the potential within the sink. These subscripts are used in the appropriate combinations as shown in Figures 1c and 1d.

When Laplace's equation is solved subject to the above boundary conditions, the following potential functions are obtained:

$$\left.\begin{aligned} U_{1A} &= \frac{I\rho'}{2\pi}\left\{\frac{1}{R}+\frac{(\rho''-\rho)'}{b}\sum_{n=0}^{\infty}\sum_{m=0}^{n}\frac{(2n+1)(2-\delta_{0m})}{(-1)^m}\left[\frac{(n-m)!}{(n+m)!}\right]^2\right. \\ &\qquad \left.\cdot\frac{K_n{}^m(\eta_1)L_n{}^m(\eta_1)}{\rho' L_n{}^m(\eta_1)-\rho'' K_n{}^m(\eta_1)}P_n{}^m(\xi_0)P_n{}^m(\xi)Q_n{}^m(\eta_0)Q_n{}^m(\eta)\cos m\phi\right\} \\ U_{2A} &= \frac{I\rho'}{2\pi}\left\{\frac{1}{R}+\frac{(\rho''-\rho')}{b}\sum_{n=0}^{\infty}\sum_{m=0}^{n}\frac{(2n+1)(2-\delta_{0m})}{(-1)^m}\left[\frac{(n-m)!}{(n+m)!}\right]^2\right. \\ &\qquad \left.\cdot\frac{L_n{}^m(\eta_1)}{\rho' L_n{}^m(\eta_1)-\rho'' K_n{}^m(\eta_1)}P_n{}^m(\xi_0)P_n{}^m(\xi)Q_n{}^m(\eta_0)P_n{}^m(\eta)\cos m\phi\right\} \end{aligned}\right\} \quad (1)$$

$$\left.\begin{aligned} U_{1B} &= \frac{I\rho''}{2\pi}\left\{\frac{1}{R}+\frac{(\rho''-\rho')}{b}\sum_{n=0}^{\infty}\sum_{m=0}^{n}\frac{(2n+1)(2-\delta_{0m})}{(-1)^m}\left[\frac{(n-m)!}{(n+m)!}\right]^2\right. \\ &\qquad \left.\cdot\frac{K_n{}^m(\eta_1)}{\rho' L_n{}^m(\eta_1)-\rho'' K_n{}^m(\eta_1)}P_n{}^m(\xi_0)P_n{}^m(\xi)P_n{}^m(\eta_0)Q_n{}^m(\eta)\cos m\phi\right\} \\ U_{2B} &= \frac{I\rho''}{2\pi}\left\{\frac{1}{R}+\frac{(\rho''-\rho')}{b}\sum_{n=0}^{\infty}\sum_{m=0}^{n}\frac{(2n+1)(2-\delta_{0m})}{(-1)^m}\left[\frac{(n-m)!}{(n+m)!}\right]^2\right. \\ &\qquad \left.\cdot\frac{1}{\rho' L_n{}^m(\eta_1)-\rho'' K_n{}^m(\eta_1)}P_n{}^m(\xi_0)P_n{}^m(\xi)P_n{}^m(\eta_0)P_n{}^m(\eta)\cos m\phi\right\} \end{aligned}\right\} \quad (2)$$

where $P_n{}^m(x)$ and $Q_n{}^m(x)$ are the associated Legendre functions of the first and second kinds, respectively; $I$ is the current strength; $R$ is the distance, without regard to sign, between the current source and the point at which the potential is to be computed; $m$ and $n$ are integers or zero; and the Krönecker delta $\delta_{0m}$ equals either 1 (if $m=0$) or zero (if $m\neq 0$). In these equations, a subscript zero on a given coordinate indicates that it is a coordinate of the point source of current. The new symbols introduced in (1) and (2) are given by:

$$K_n{}^m(x) = \frac{P_n{}^m(x)}{Q_n{}^m(x)} \quad (3)$$

$$L_n{}^m(x) = \frac{P_n{}'^m(x)}{Q_n{}'^m(x)}\,. \quad (4)$$

Consider next a spheroidal sink whose boundary is described by $\zeta=\zeta_1$ in oblate spheroidal coordinates. It can be shown that the correct potential functions for this problem can be obtained from the above equations by multiplying each summation by the imaginary number $i$ and by making the following substi-

tutions:

$$\left.\begin{aligned}\eta &\rightarrow i\zeta \\ \xi &\rightarrow \mu\end{aligned}\right\}. \tag{5}$$

Since the resulting equations are obvious, these new potential functions are not written down explicitly here.

Even less exactly than above, a filled sink can be approximated by a hemispherical shape, in which case spherical coordinates are used (Fig. 1a). The boundary of the sink is designated $r=r_1$, and the resistivity designations remain the same as before. The surface of the earth is taken as the plane $\phi=0, \pi$. The potential function $U$ can be obtained either directly by solving Laplace's equation in spherical coordinates or indirectly by treating the sphere as the limiting case of a spheroid and manipulating the potential function given in terms of prolate spheroidal coordinates. Either method gives the following potential function for the case of the hemispherical sink:

$$\left.\begin{aligned}U_{1A} &= \frac{I\rho'}{2\pi}\left\{\frac{1}{R}+\beta_{21}\sum_{n=0}^{\infty}\frac{n r_1^{2n+1}}{(n+\alpha_{21})(r_0 r)^{n+1}}P_n(\cos\theta)\right\} \\ U_{2A} &= \frac{I\rho'}{2\pi}\left\{\frac{\alpha_{21}}{r_0}\sum_{n=0}^{\infty}\frac{2n+1}{n+\alpha_{21}}\left(\frac{r}{r_0}\right)^n P_n(\cos\theta)\right\} \\ U_{1B} &= \frac{I\rho''}{2\pi}\left\{\frac{\alpha_{12}}{r}\sum_{n=0}^{\infty}\frac{2n+1}{n+\alpha_{21}}\left(\frac{r_0}{r}\right)^n P_n(\cos\theta)\right\} \\ U_{2B} &= \frac{I\rho''}{2\pi}\left\{\frac{1}{R}+\beta_{12}\sum_{n=0}^{\infty}\frac{n+1}{n+\alpha_{21}}\frac{(r_0 r)^n}{r_1^{2n+1}}P_n(\cos\theta)\right\}\end{aligned}\right\} \tag{6}$$

where

$$\left.\begin{aligned}\alpha_{ij} &= \frac{\rho_i}{\rho_i+\rho_j} \\ \beta_{ij} &= \frac{\rho_i-\rho_j}{\rho_i+\rho_j}\end{aligned}\right\}. \tag{7}$$

$\beta_{ij}$ is identical to the "reflection factor" of Roman and $2\alpha_{ij}$ is identical to the "reflection complement" of Roman (1933, p. 122). Also $\beta_{ij}$ is equivalent to the "$k$" or "$-k$" used by Tagg (1930), depending on the assignment of $\rho'$ and $\rho''$.

The line joining the current electrode $I$ and the center of the hemispherical sink (Fig. 2) is taken as the polar axis, which consequently rotates as the current electrode moves along the traverse. $r$ and $r_0$ are the distances from the center of the hemisphere to the potential electrode and current electrode, respectively; $r_1$ is the radius of the hemisphere; $\theta$ is the angle subtended at the origin by the line

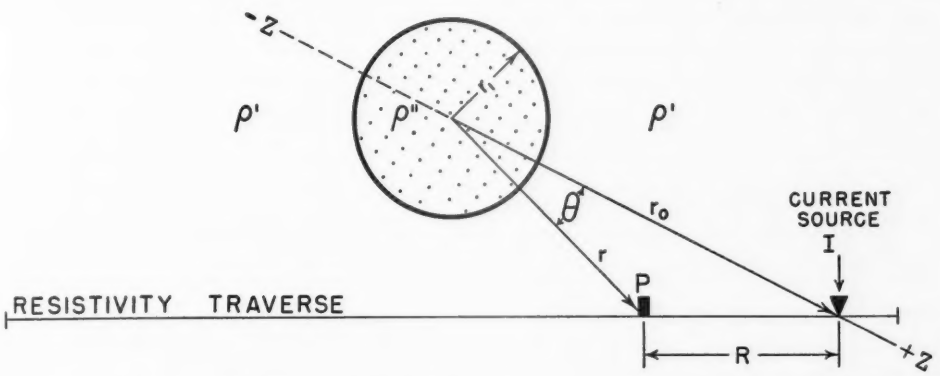


FIG. 2. Plan view of hemispherical sink showing relationship with an arbitrary resistivity traverse. The plane of this figure corresponds to $xz$-plane in Figure 1a.

drawn between the current and potential electrodes; and $P_n$ (cos $\theta$) is the Legendre polynomial. All other symbols are identical with those defined above for spheroids.

*Vertical Faults and Dikes*

It will be shown in a later section that, under certain circumstances, the resistivity effect of a sink can be approximated by the resistivity effect of a vertical dike or a pair of vertical faults. The basic theory to obtain the potential functions in the case of vertical faults has been given by Tagg (1930) and others. Moreover, the theoretical treatments by Stefanesco et al. (1930), Roman (1933), and others for horizontal discontinuities can, with only slight modification, be used to obtain the resistivity curves for the faults and dikes to be presented in this paper.[2] Therefore the details of these solutions are not included in the brief treatment given here.

*Apparent Resistivity for Lee and Wenner Configurations*

The Lee configuration consists of two outer current electrodes $C_1$ and $C_2$ that are spaced a distance of $3a$ apart (Fig. 3). Potential electrodes $P_1$ and $P_2$ are so located on the line connecting $C_1$ and $C_2$ that they divide the line into three equal segments of length $a$, which is designated the electrode separation. A third potential electrode, $P_0$, is placed midway between $P_1$ and $P_2$. From the potential differences $V_{10}$ and $V_{02}$ (Fig. 3), which are measured between the pairs $P_1P_0$ and $P_0P_2$, respectively, the two apparent resistivities $\rho_1$ (for the right-hand side of the Lee partitioning plane) and $\rho_2$ (for the left-hand side) are obtained respectively from the equations:

[2] A theoretical treatment of the resistivity effects over a vertical discontinuity is presented by Logn in a paper that appears on p. 739–760 of this issue of GEOPHYSICS—*The Editor*.

$$\left.\begin{aligned}\rho_1 &= 4\pi a \frac{V_{10}}{I} \\ \rho_2 &= 4\pi a \frac{V_{02}}{I}\end{aligned}\right\}. \tag{8}$$

$I$ is the current flowing between $C_1$ and $C_2$.

The Wenner configuration differs from the Lee configuration in that potential electrode $P_0$ is omitted. From the potential difference $V_{12}$, which is measured be-

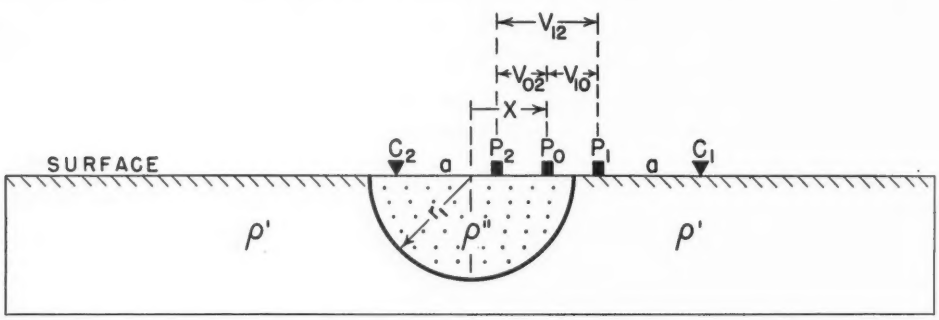


FIG. 3. Lee configuration showing convention of electrode designations and potential differences.

tween the pair $P_1P_2$ (Fig. 3), the one apparent resistivity $\rho_a$ is obtained by the equation:

$$\rho_a = 2\pi a \frac{V_{12}}{I}. \tag{9}$$

The station is considered to be the position of $P_0$ for the Lee configuration (Fig. 3) and the midpoint between $P_1$ and $P_2$ for the Wenner configuration (Fig. 5g).

## INTERPRETATION OF HORIZONTAL RESISTIVITY PROFILES

The horizontal resistivity profile, as the term is used in the present paper, is obtained by moving the electrode configuration in a straight line, keeping constant the distances between the electrodes. The horizontal profile is sometimes designated by "traverse profile" (Hubbert, 1934, p. 12), "electrical trenching" (Hedström, 1932), and various other terms. The distance between two successive stations in horizontal profiling is designated the station interval.

### *Theoretical Horizontal Resistivity Profiles Over Hemispherical Sink*

*Lee Configuration.*—Theoretical horizontal profiles over a filled hemispherical sink for the Lee configuration are shown in Figure 4. The electrode separation, $a$, is taken as half the radius of the hemisphere, and the resistivity of the material in the sink is one-fifth the resistivity of the surrounding medium. To facilitate

the use of the charts for general values of resistivity, subject only to the constant resistivity contrast of 1 to 5, the resistivity values are plotted as ordinates in terms of the ratio of the apparent resistivity to the true resistivity of the medium outside the sink. The apparent resistivities on the right and left sides of the Lee partitioning plane are designated by $\rho_1$ and $\rho_2$, respectively. In the charts a solid line indicates the values of $\rho_1/\rho'$, and a dashed line indicates those of $\rho_2/\rho'$. The ratio of apparent to true resistivity as used here is comparable to the "disturbing factor" of Roman (1933, p. 193), and is a dimensionless factor. The apparent resistivity is obtained by multiplying this factor by the true resistivity ($\rho'$) of the country rock. Since the resulting curves of this plotted factor can be visualized for convenience as apparent resistivity curves, the terms "apparent resistivity values" and "values of the ratio $\rho_1/\rho'$ (or $\rho_2/\rho'$, or $\rho_a/\rho'$)" are often used interchangeably in this paper. Strictly, however, the apparent resistivity is equal to the factor $\rho_1/\rho'$ (or $\rho_2/\rho'$, or $\rho_a/\rho'$) only when the true resistivity $\rho'$ is unity.

Because it is convenient to use dimensionless quantities, distances along the traverses are plotted in terms of the electrode separation $a$ and in accordance with the convention of Fig. 4g.

The apparent resistivity values are plotted by the "offset plotting" technique, which is customarily used in the field for the Lee partitioning method. In each case, the value of $\rho_1/\rho'$ is plotted against the position of the midpoint of the line connecting $P_0$ and $P_1$. Similarly, the value of $\rho_2/\rho'$ is plotted against the corresponding position of the midpoint of the line joining $P_0$ and $P_2$. It should be emphasized that for the Lee configuration the apparent resistivities are not plotted against the "station" at which they are determined, that is, the position of the center electrode $P_0$.

For traverse 1 (Fig. 4a), which is taken over the center of the sink, each of the apparent resistivity curves along the horizontal profile displays eight separate discontinuities in slope. Each discontinuity correlates exactly with a position at which either a current electrode or a potential electrode crosses the boundary of the sink. Two maxima and two minima lying on either side of the sink are important features that characterize the horizontal traverse over the filled sink. On the left side of the sink the pronounced peak $A$ and the accompanying lesser peak $A'$ lying directly below it (Fig. 4a) lie at a distance of $a/4$ outside of the boundary of the sink. Peak $A$ occurs as the potential electrode $P_0$ crosses the left edge of the sink and peak $A'$ occurs as the potential electrode $P_1$ crosses the same edge of the sink. These two maxima, together with their maxima counterparts $B$ and $B'$ on the right side of the sink, greatly facilitate the interpretation of the location of the edges of the filled sink. The minimum at $C$ lies at a distance of $7a/4$ to the left of the boundary, and the minimum at $C'$ lies at a distance of $5a/4$ to the left of the boundary. Thus the two minima $C$ and $C'$, which occur as the current electrode $C_1$ crosses the left edge of the sink, are separated by a distance of $a/2$. A corresponding relationship exists between the two minima $D$ and $D'$ lying on the east edge of the sink.

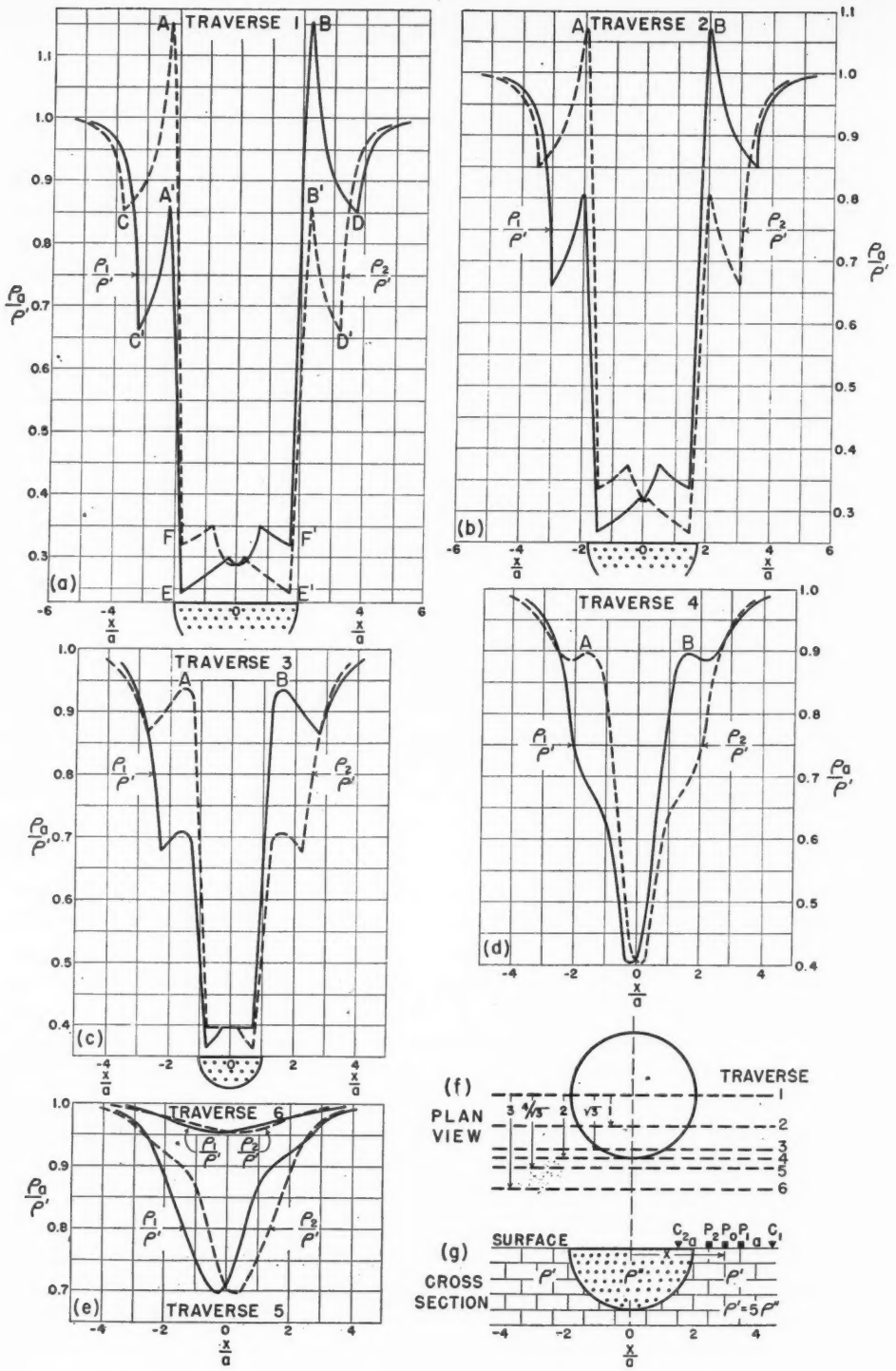


FIG. 4. Theoretical horizontal resistivity profiles over hemispherical sink at different distances from center of sink, Lee configuration (offset plotting). Cross sections taken along resistivity traverses. Diameter of hemisphere $=4a$ (sink size is same in each case). $\rho''/\rho'=\frac{1}{5}$.

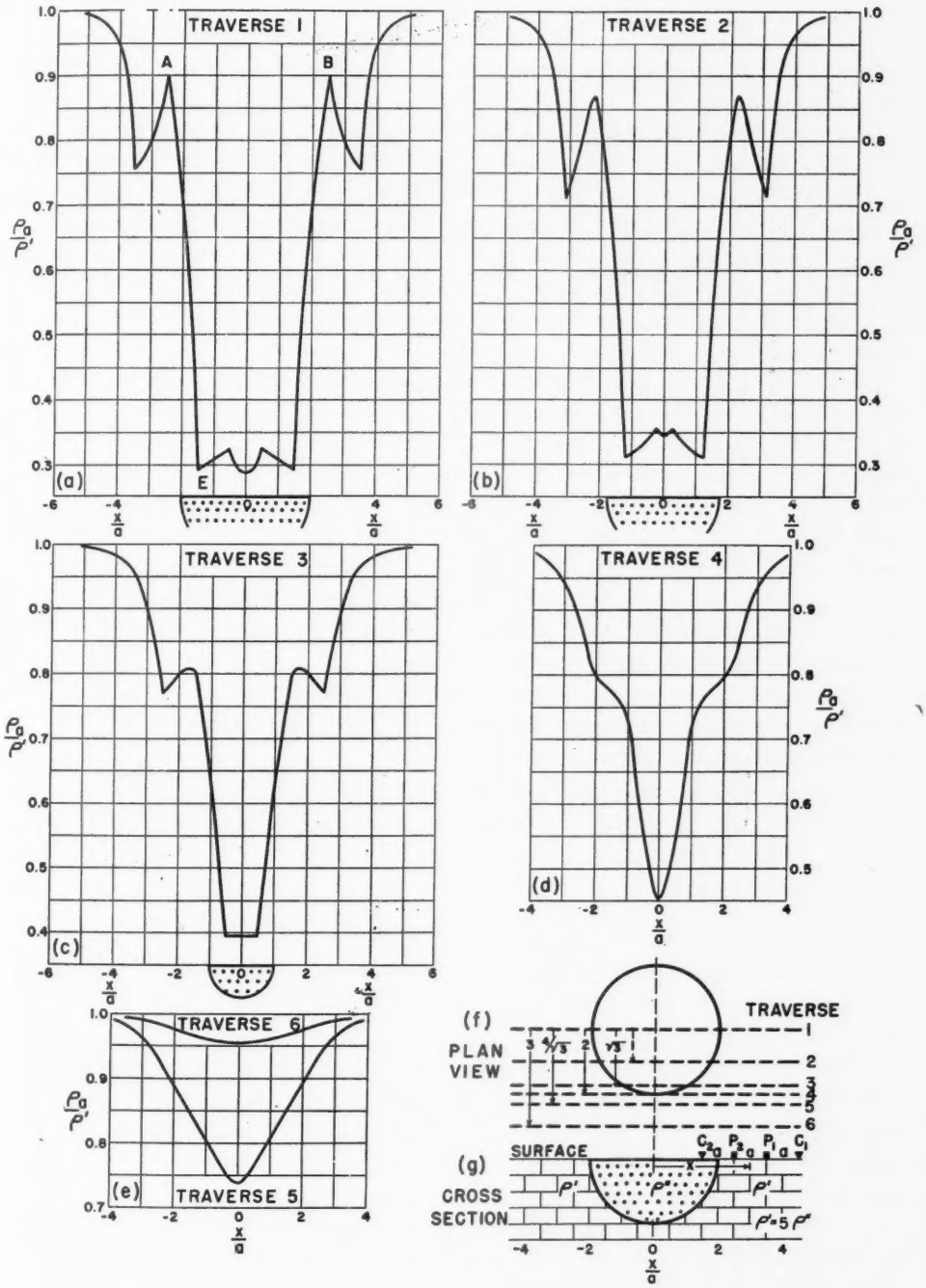


FIG. 5. Theoretical horizontal resistivity profiles over hemispherical sink at different distances from center of sink, Wenner configuration. Cross sections taken along resistivity traverses. Diameter of hemisphere $=4a$ (sink size is same in each case). $\rho''/\rho' = \frac{1}{5}$.

On traverse 1 (Fig. 4a), the distance between peaks $A$ and $B$, or between peaks $A'$ and $B'$, is equal to the sum of the diameter of the sink plus half the electrode separation $a$.

The deep resistivity trough that lies over the central part of the sink is a very diagnostic feature. Here the apparent resistivity values decrease to minima at $E$ and $E'$ (Fig. 4a). The gradient of the curve is steep, the total change from the peak at $A$ to the minimum at $F$ occurring over a horizontal distance of half the electrode separation $a$. At the geometric center of the sink, the $\rho_1/\rho'$ and $\rho_2/\rho'$ curves cross each other symmetrically, and the point of symmetrical crossing is an important interpretative feature except in those cases where field "noise" limits or vitiates its usefulness.

Contrasting features exist between horizontal traverses that cross the sink at different distances from the center. Except for traverse 1, which crosses the center of the sink, the peaks at $A$ and $B$ (Figs. 4b to 4d) display no discontinuity in slope. These peaks persist as maxima through traverse 4 (tangent), and influence the shape of the curves even beyond, actually disappearing only as the anomaly itself becomes very small. Successive traverses at increasing distances from the center of the sink indicate that the distance between peaks $A$ and $B$ diminishes as one goes further from the center. Minima comparable to those at $C$, $C'$, $D$, and $D'$ (Fig. 4a) exist for other traverses that cross the sink (Fig. 4b and 4c) but disappear for traverses lying outside of the sink.

Although the various maxima and minima that occur in the bottom of the resistivity trough are of academic interest, they are generally too small to be of practical assistance to the interpreter.

*Anomaly Index.*—In analysis of the theoretical resistivity data for the Lee configuration, the *anomaly index* as used by us is defined as the maximum value of $\rho_1/\rho'$ minus the minimum value of $\rho_1/\rho'$. In the case of the Lee field data, the anomaly index is the ratio:

$$(\rho_{1\,\max} - \rho_{1\,\min})/\rho_{1\,\text{regional}}.$$

Similar indices apply to the values of $\rho_2$. Also similar indices apply for the Wenner configuration by replacing, in the definition, $\rho_1/\rho'$ by $\rho_a/\rho'$ or $\rho_1$ by $\rho_a$ for theoretical or field data, respectively.

This index number is comparable in some respects to indices already suggested by Lee and Hemberger (1946) and Guyod (1944) for resistivity anomalies. It is to be understood that the "maximum value" as used may sometimes be the regional value itself as, for example, when the value of the peak at $A$ (Fig. 4c) falls below the regional value.

The anomaly index is introduced in order to facilitate comparison of curves. In general, the configuration and the traverses chosen in an actual survey will be such that the index will probably be a maximum.

For traverse 1 (Fig. 4a) the anomaly index, which is the same for both $\rho_1$ and

$\rho_2$, is equal to 1.15−0.24=0.91. The anomaly indices for all traverses across the hemisphere in Figure 4 are given in Table I.

*Wenner Configuration.*—Theoretical horizontal profiles over a filled hemispherical sink for the Wenner configuration are shown in Figure 5. The electrode separation $a$, locations of the traverses, dimensions of the sink, and resistivity contrast are all the same as in the example discussed above in which the Lee configuration was used. For the Wenner data, the apparent resistivities are plotted against the station at which they are determined, that is, at the center of the Wenner configuration used to obtain each data point.

TABLE I

COMPARISON OF ANOMALY INDICES FOR LEE AND WENNER CONFIGURATIONS FOR HORIZONTAL PROFILES OVER HEMISPHERICAL SINK

| Traverse | Lee | Wenner | Ratio Lee/Wenner |
|---|---|---|---|
| 1 | 0.912 | 0.712 | 1.28 |
| 2 | 0.792 | 0.692 | 1.14 |
| 3 | 0.637 | 0.605 | 1.05 |
| 4 | 0.597 | 0.546 | 1.09 |
| 5 | 0.306 | 0.261 | 1.17 |
| 6 | 0.048 | 0.044 | 1.10 |

*Comparison of Theoretical Results—Lee and Wenner Configurations.*—Although the general features of the peaks and troughs in the curves for the Wenner configuration are similar to those for the Lee configuration, important specific differences exist. For traverse 1 (Fig. 5a), each peak, $A$ or $B$, for the Wenner configuration lies at a distance of $a/2$, rather than $a/4$, outside of the boundary of the sink; and the distance between the peaks is equal to the sum of the diameter of the sink plus the whole electrode separation $a$, rather than half the electrode separation as in the case of the Lee configuration.

The gradient of the curve at the edge of the resistivity trough is less steep for the Wenner configuration than for the Lee configuration, the total change from the peak at $A$ to the minimum at $E$ (Fig. 5a) occurring over a horizontal distance equal to the electrode separation $a$, rather than $a/2$ as in the case of the Lee configuration.

The magnitude of the features for the Wenner configuration is damped in comparison with the Lee configuration. In great contrast with the apparent resistivity as measured by the Lee configuration in this particular example, none of the apparent resistivity values measured by the Wenner configuration rises above the value of the highest true resistivity represented.[3] Consequently the anomaly index for the Wenner configuration is less than that for the Lee configuration (see

[3] In a few exceptional cases, the Wenner resistivity does rise slightly above the highest true resistivity.

Table I). This fact is made clearer in the last column in Table I, which gives the ratios of the anomaly indices for the Lee configuration to those for the Wenner configuration. Apparently the ratio is always greater than one.

*Field Example of Horizontal Resistivity Profiles Over Filled Sink*

*Lee Configuration.*—In Figure 6, a typical field horizontal profile obtained with the Lee configuration over a known shale sink in Cherokee County, Kansas, is compared with two theoretical horizontal profiles over a hemispherical sink. The electrode separation $a$ is 100 feet, and the spacing between successive stations is 50 feet. In all the diagrams, the offset method of plotting is used and the same scales for resistivity and for horizontal distance are used. In order to show the geologic details better, the vertical scale in the geologic cross section in Figure 6b is made three times the horizontal scale; in the geologic cross sections in Figures 6a and 6c, the horizontal and vertical scales are equal. Except for the easternmost part of the $\rho_2$ curve, the field horizontal profile shown in Figure 6b is typical of that for a filled sink.

It is shown above (Fig. 4a) that, for a continuous theoretical curve for a horizontal profile crossing the center of a hemispherical sink, the west margin of the sink lies at a distance of $a/4$, or 25 feet in this case, east of peak $A$ and similarly that the east margin lies 25 feet west of peak $B$. The peaks $A$ and $B$ on the field horizontal profile (Fig. 6b) lie 200 feet apart. Therefore, a filled sink with a diameter of 150 feet is postulated, with certain reservations that are discussed below.

Measurements made in adjacent areas, where excellent geologic control is available, indicate that a resistivity contrast of about 1 to 5 exists between the shale and limestone; and a similar ratio is therefore assumed in computing the theoretical curves of Figure 6.

Figure 6a shows a continuous theoretical curve for a filled hemispherical sink with an assumed diameter of 150 feet and a ratio of the resistivity of the material inside the sink to that of the material outside the sink taken as 1 to 5, respectively. The theoretical profile crosses the center of the sink. A proportionality factor of 50 ohm-meters is introduced in order to make the theoretical resistivity values comparable in magnitude to the observed field resistivity values, i.e. so that $\rho''/\rho' = 50/250$.

A theoretical field plot, or field plot of the theoretical data, is shown in Figure 6c. By definition, the theoretical field plot is obtained from the continuous theoretical curve (Fig. 6a) by taking discrete points from the continuous curve and connecting them with straight lines. The spacing of the discrete points is made to conform to the station interval along the horizontal resistivity traverse in the field. In the present example the interval is $a/2$. In order to obtain the closest correspondence between the theoretical field plot and the actual field curve, a template with vertical slits, separated by a scale distance equal to $a/2$ and representing the plotted positions of $\rho_1$ and $\rho_2$, is moved along the continuous

theoretical profile. In the present example the closest correspondence between the theoretical field plot and actual field plot is obtained in this manner when the plotted points on the theoretical field plot (Fig. 6c) lie 5 feet to the east of the center of the continuous theoretical curve (Fig. 6a). Greater shifts of the configuration in either direction from that chosen in Figure 6c result in theoretical field plots that depart to a greater degree from the observed field profile shown in figure 6b. For this reason, the center of the hemisphere in Figure 6c is shifted 5 feet to the west of the point midway between peaks *A* and *B*.

It should be emphasized that any theoretical field plot derived from the continuous theoretical curve in Fig. 6a exhibits sharp peaks, corresponding to peaks *A* and *B* (Fig. 6c), which lie exactly 200 feet apart. Moreover, for any Lee configuration traverse crossing the center of a hemispherical sink whose diameter is an integral multiple of $a/2$, the distance between the highest peaks on the theoretical field plot (offset plotting) is equal to the diameter of the sink plus half the electrode separation $a$. The same rule would apply for all sinks if the points on the field curve were infinitesimally close together. However, for any sink of diameter differing from an integral multiple of $a/2$, the distance between the peaks will vary according to the station interval taken and the locations of the stations in relation to each edge of the sink. Because the ambiguity as to the exact location of the margins of the sink lying between the peaks is related to the spacing of the resistivity stations, the precision of location of the margins of the sink can be increased by taking the stations closer together in the critical regions. Because the results of the horizontal profile method are very sensitive to the location of the edges of the sink, the additional information obtained by smaller spacing of the stations is often worth the extra time and trouble.

When the usual irregularities of the field data are discounted, the correlation of the theoretical (Fig. 6c) and the field (Fig. 6b) curves is considered to be excellent. The theoretical considerations and interpretative rules outlined above greatly facilitate the testing of shale sinks to obtain a maximum amount of information with a minimum amount of drilling.

*Wenner Configuration.*—In Figure 7 the field horizontal profile that would be obtained with the Wenner configuration over the same known shale sink is compared with two theoretical horizontal profiles over a hemispherical sink as before. The Wenner apparent resistivity values are plotted in the usual manner at the station occupying the midpoint between $P_1$ and $P_2$. Although the spacing between successive stations for horizontal profiles with the Wenner configuration is often taken as the whole electrode separation $a$, the spacing is taken as $a/2$ in the present example in order that a fair comparison can be made between the Lee and Wenner configurations.

*Comparison of Field Results—Lee and Wenner Configurations.*—In the field example just given, the size of the peaks and the troughs is less pronounced for the Wenner configuration than for the Lee configuration. The anomaly indices, given in Table II, indicate the differences quantitatively. It should be emphasized that,

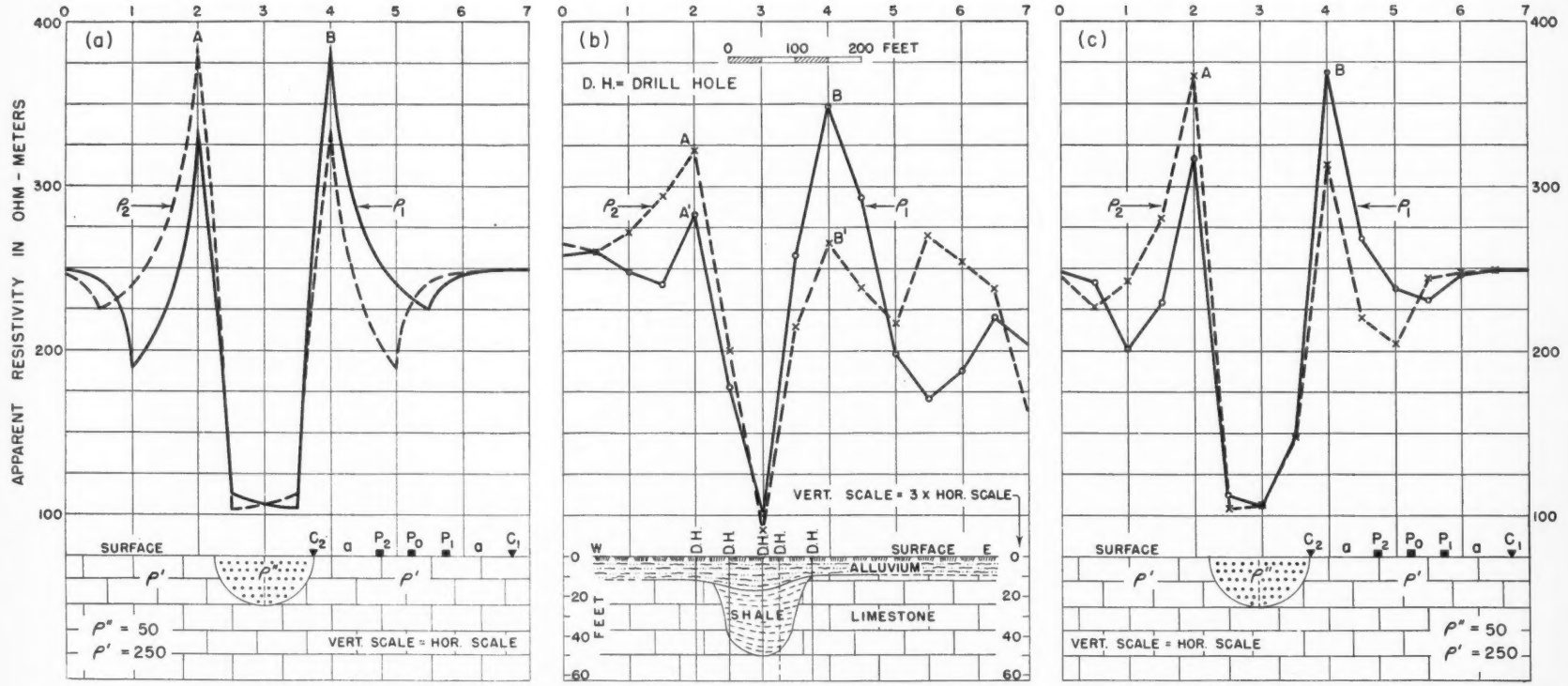


FIG. 6. Comparison of theoretical and observed horizontal resistivity profiles over filled sink, Lee configuration (offset plotting). (a) Continuous theoretical curve over hemispherical sink. (b) Observed field curve with geologic cross section. (c) Theoretical field plot over hemispherical sink. Assumed diameter of sink $= 3a/2$. Assumed $\rho''/\rho' = 50/250$.

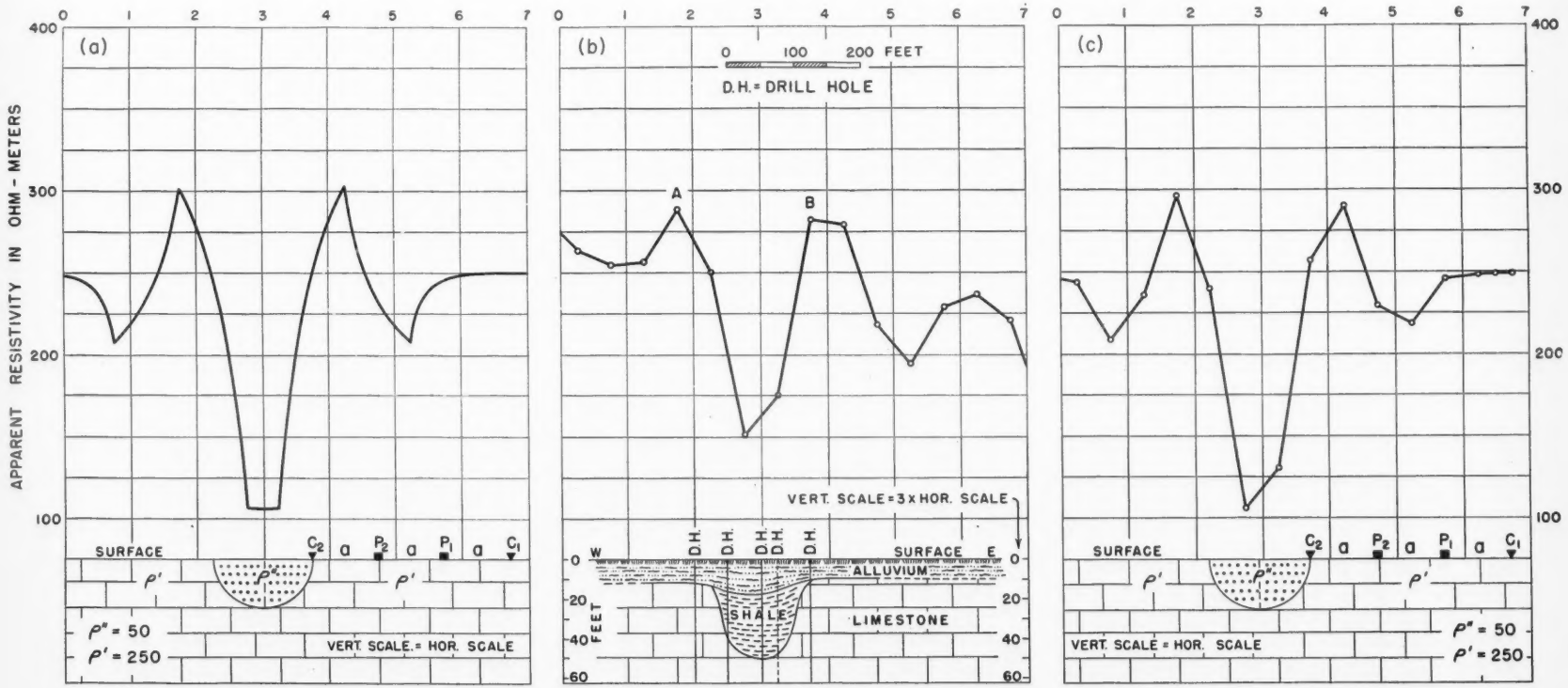


FIG. 7. Comparison of theoretical and observed horizontal resistivity profiles over filled sink, Wenner configuration. (a) Continuous theoretical curve over hemispherical sink. (b) Observed field curve with geologic cross section. (c) Theoretical field plot over hemispherical sink. Assumed diameter of sink $= 3a/2$. Assumed $\rho''/\rho' = 50/250$.

TABLE II

COMPARISON OF ANOMALY INDICES OVER FILLED SINK. THEORETICAL CONTINUOUS CURVE AND THEORETICAL FIELD PLOT FOR HEMISPHERE COMPARED WITH ACTUAL FIELD CURVE
(Assumed regional value of apparent resistivity equals 250 ohm-meters)

| Curve | Anomaly indices | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Lee configuration | | | Wenner configuration | | | Ratio, Lee/Wenner | | |
| | $\rho_1$ | $\rho_2$ | Average | West peak | East peak | Average | $\rho_1$/Wenner west peak | $\rho_2$/Wenner east peak | Average |
| Theoretical continuous curve | 1.13 | 1.13 | 1.13 | 0.79 | 0.79 | 0.79 | 1.44 | 1.44 | 1.44 |
| Theoretical field plot | 1.05 | 1.05 | 1.05 | 0.76 | 0.74 | 0.75 | 1.37 | 1.43 | 1.40 |
| Actual field curve | 0.99 | 0.92 | 0.96 | 0.55 | 0.52 | 0.54 | 1.80 | 1.77 | 1.79 |

for either the Lee or Wenner configuration, the anomaly indicies of both the theoretical field plot and also the actual field curve are dependent partly on the locations of the stations in relation to the locations of the edges of the sink. For this reason, the east and west values of the anomaly index are generally unequal.

Because of the modification of peak *B* in the field curve it is difficult to assign a value for the probable width of the sink from the Wenner curve alone. Thus an inherent weakness in the Wenner configuration, as used for making width determinations, arises from the possibility that one (or both) of the two peaks may be indefinite, in which case the width cannot be accurately determined. The analysis indicates further that if the Wenner method is used, a spacing of $a/2$ or less between successive stations is desirable for even approximately outlining a sink, rather than a spacing of $a$. With the Lee configuration, on the other hand, even though one of the two major peaks *A* and *B* (Fig. 6b) were indefinite, there is still a high probability that the subsidiary peaks $A'$ and $B'$ would be sufficiently pronounced to aid in the interpretation of both the width of the sink and the location of the margins of the sink.

The additional resolving power of the Lee configuration in comparison with the Wenner configuration indicates that for the same number of stations taken along the same horizontal profile, the Lee method can give more detailed information than the Wenner method. Moreover, in certain ambiguous cases—especially in areas where the sinks are small—this additional information will lead the interpreter to recognize sink features on the Lee profiles that are not recognizable on the Wenner profiles.

*Effect of Overburden.*—Although the mantle of soil and alluvium tempers the resistivity anomalies to some degree, the peaks discussed above are still very pronounced in the observed field curves, especially in the case of the Lee configuration. In the cross sections shown in Figures 6b and 7b, the thickness of the alluvium averages about 12 feet and apparently attains a maximum thickness of about 17 feet directly over the sink.

*Value of Various Approximations*

Filled sinks occur in the field with a wide range of shapes, dimensions, and resistivity contrasts. One of the problems in interpreting resistivity data over filled sinks is to recognize what approximations can be made in order to fit the theoretical data satisfactorily to the field data. Computations of the theoretical resistivity anomalies over hemispheroidal or hemispherical sinks are so tedious that shortcuts or reasonable approximations in interpretational procedures are highly desirable.

To give some notion of the types of approximations that can be made, a comparison of the theoretical results of horizontal resistivity profiles using the Lee and Wenner methods over an oblate hemispheroidal sink, a hemispherical sink, a vertical dike, and a pair of faults without considering their mutual interaction is given in Figures 8 and 9 respectively. In each case the resistivity contrast of the material inside the sink, dike, or faults to the material outside is taken as 1:5. The diameter of the hemisphere is taken as $3a/2$, where $a$ is the electrode separation. The length of the major axis of the oblate hemispheroid, which is circular in plan view at the surface, is $3a/2$; and the length of the semi-minor axis, which is the vertical axis of rotation, is $3a/8$. The width of the dike and the distance between the faults are taken as $3a/2$. The dike and faults are assumed to be of infinite length in the direction of strike and of infinite depth extent.

The horizontal profile is taken along the major axis and diameter, respectively, in the case of the oblate hemispheroid and the hemisphere, and along a line perpendicular to the strike in the case of the dike and the faults. Thus in each case the horizontal traverse crosses the same width ($3a/2$) of low-resistivity medium. It should be emphasized that the theoretical anomaly over each of the faults is for a single fault with no other fault lying in the vicinity. Two such faults and their respective anomalies are merely moved into juxtaposition so that they are separated by a distance of $3a/2$ and can be compared with the other bodies.

The curves of Figures 8 and 9 are similar in the following respects:

(1) The general appearance of all curves is the same. The discontinuities in slope of each curve of the Lee set occur at identical points. The same is true within the Wenner set of curves, but the corresponding points in the two sets do not coincide.

(2) Each curve shows a pronounced low-resistivity anomaly over the low-resistivity medium and approaches regional resistivity asymptotically at great distances from the low-resistivity medium.

(3) The Lee curves for $\rho_1/\rho'$ and $\rho_2/\rho'$ cross at the center of the low-resistivity medium.

The curves differ in the following respects:

(1) In the central part of the low-resistivity medium, the slopes of the curves differ somewhat because of the different depths and shapes of the bottoms of the low-resistivity media.

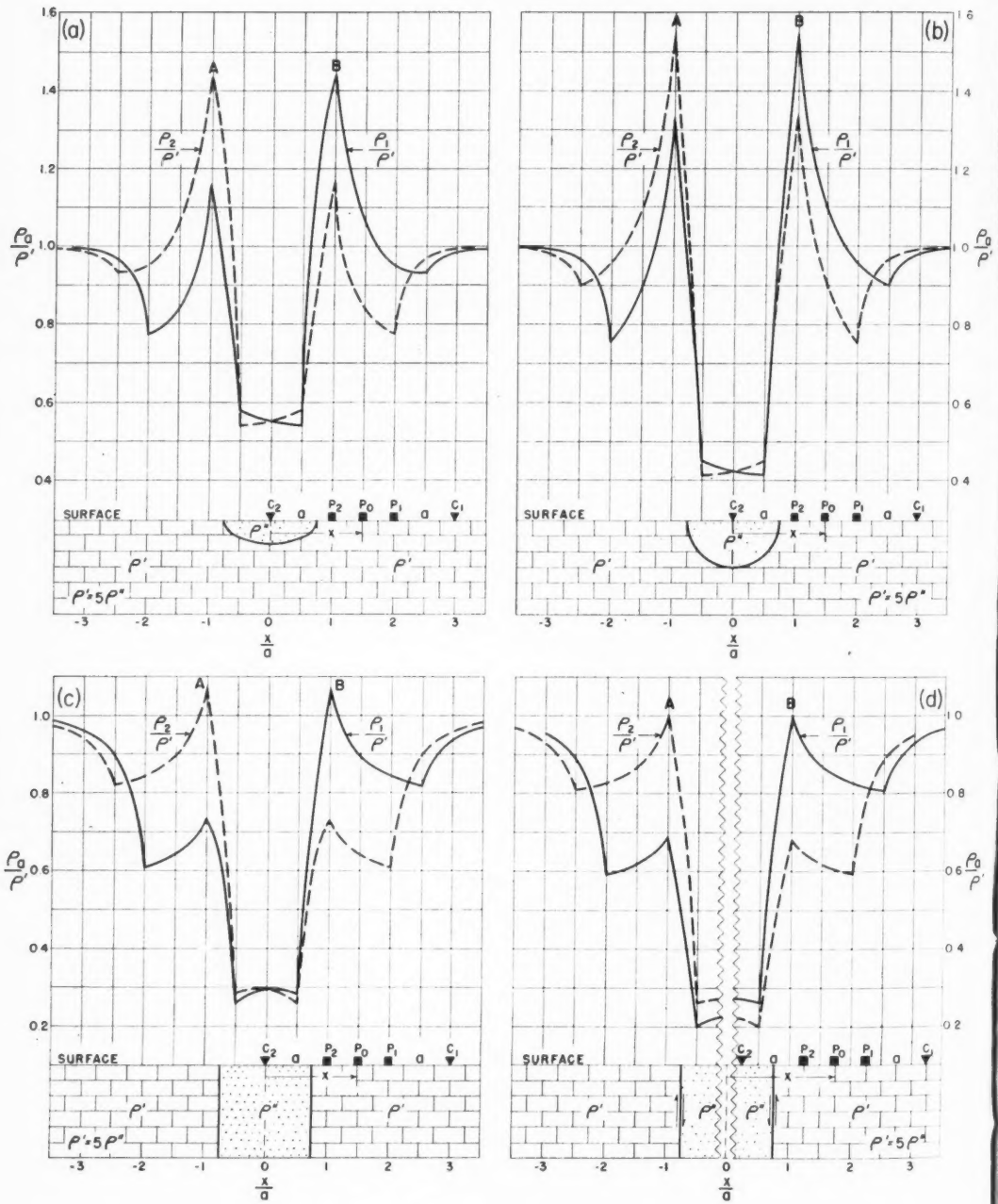


FIG. 8. Comparison of theoretical horizontal resistivity profiles over (a) oblate hemispheroid, (b) hemisphere, (c) dike, and (d) pair of faults, Lee configuration (offset plotting). Width at surface $= 3a/2$, $\rho''/\rho' = \frac{1}{5}$.

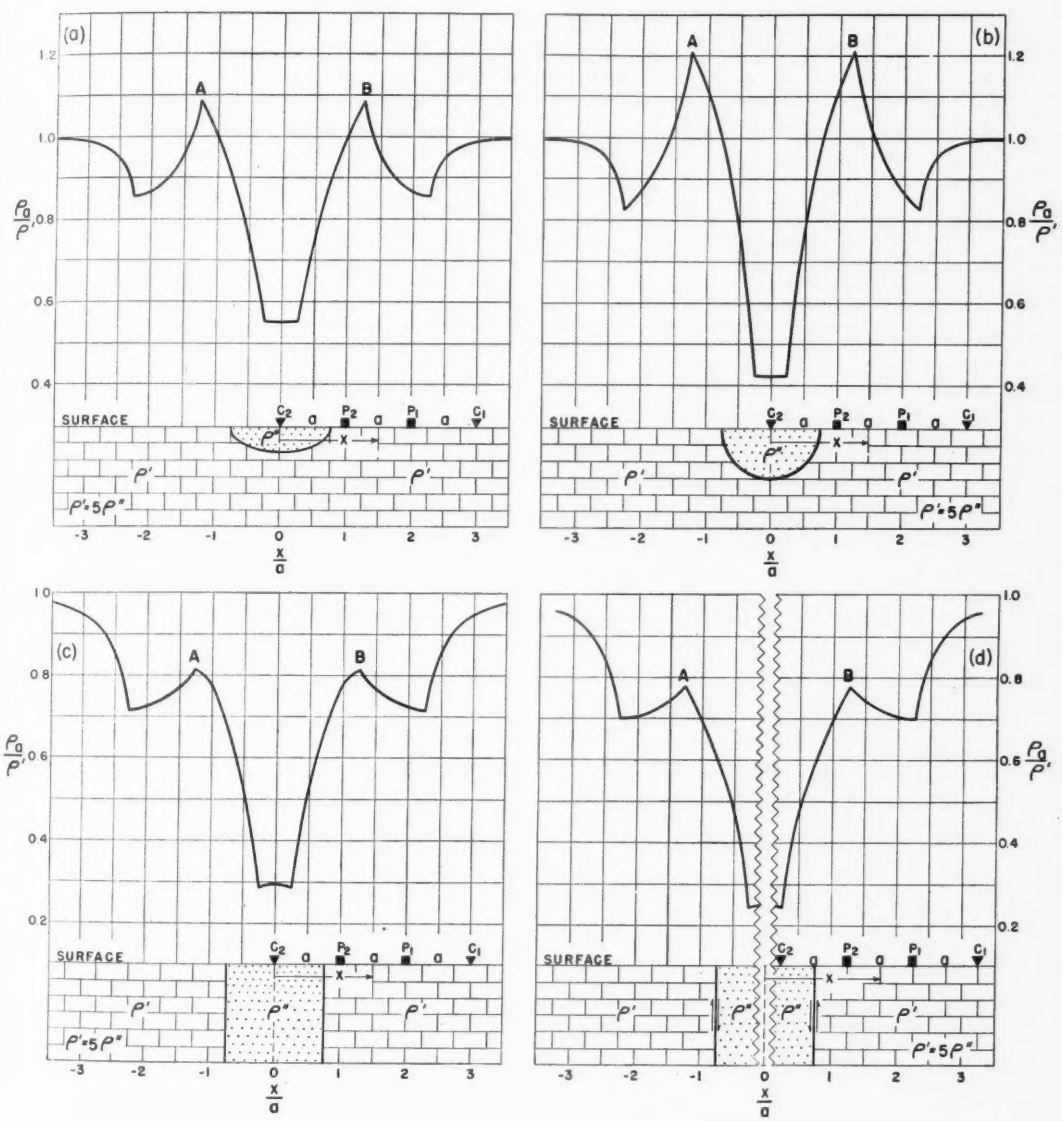


FIG. 9. Comparison of theoretical horizontal resistivity profiles over (a) oblate hemispheroid, (b) hemisphere, (c) dike, and (d) pair of faults, Wenner configuration. Width at surface $=3a/2$, $\rho''/\rho'=\frac{1}{5}$.

(2) The magnitudes of the theoretical anomalies differ with regard to maxima, minima, and hence anomaly indices. The maximum value of $\rho_a/\rho'$ is 1 for the faults and greater than 1 for the other bodies, except for the Wenner curves over the dike. The minimum value of $\rho_a/\rho'$ for the various features decreases progres-

TABLE III

COMPARISON OF ANOMALY INDICES FOR OBLATE HEMISPHEROID, HEMISPHERE, DIKE, AND PAIR OF FAULTS

| Figure | Anomaly index | | |
|---|---|---|---|
| | Lee configuration | Wenner configuration | Ratio, Lee/Wenner |
| Oblate hemispheroid | 0.90 | 0.53 | 1.70 |
| Hemisphere | 1.13 | 0.79 | 1.43 |
| Dike | 0.81 | 0.71 | 1.14 |
| Pair of faults | 0.80 | 0.76 | 1.05 |

sively in the following order: hemispheroid, hemisphere, dike, pair of faults. The anomaly indices are given in Table III.

The following generalizations can be made:

(1) The distance between peaks $A$ and $B$ is equal to the width of the body plus either (1) half the electrode separation in the case of the Lee configuration or (2) the full electrode separation in the case of the Wenner configuration.

(2) In each case, peaks $A$ and $B$ lie at a distance of $a/4$ outside of the margin of the body in the case of the Lee curves and a distance of $a/2$ outside of the margin of the body in the case of the Wenner curves.

The following approximations can be made for a horizontal profile that crosses a sink near its center:

(1) If the width of the sink is small in comparison with its length and depth extent, the edge effects are approximately those due to a vertical dike.

(2) If the sink is large in comparison with the electrode separation, the edge effects of the sink are approximately those due to a vertical fault.

## INTERPRETATION OF VERTICAL RESISTIVITY PROFILES

The vertical resistivity profile, as the term is used in the present paper, is obtained by expanding the configuration along a straight line while keeping fixed the center point, $P_0$, of the configuration. The vertical profile is sometimes called a depth profile, or an electrical drilling profile.

### *Theoretical Vertical Resistivity Profiles Over Hemispheroidal Sink*

Figure 10 shows the vertical profiles obtained along a traverse $TT'$ over the center of a set of filled sinks taking the forms of a prolate hemispheroid ($A$, Fig. 10), a hemisphere ($B$), and an oblate hemispheroid ($C$) respectively. Since the traverse $TT'$ coincides with the axis of revolution of each of the theoretical sinks, the vertical cross section of each of the sinks along the line $SS'$, which is perpendicular to the traverse, is circular. The vertical cross sections of the sinks along traverse $TT'$ are semi-elliptical for sinks $A$ and $C$ and semicircular for sink $B$. For sink $A$ the major axis of the ellipse is parallel to traverse $TT'$ and for sink $C$ the major axis is perpendicular to traverse $TT'$. If the radius of the hemisphere is taken as unity, the proportion of the three radii of revolution is $r_A:r_B:r_C$

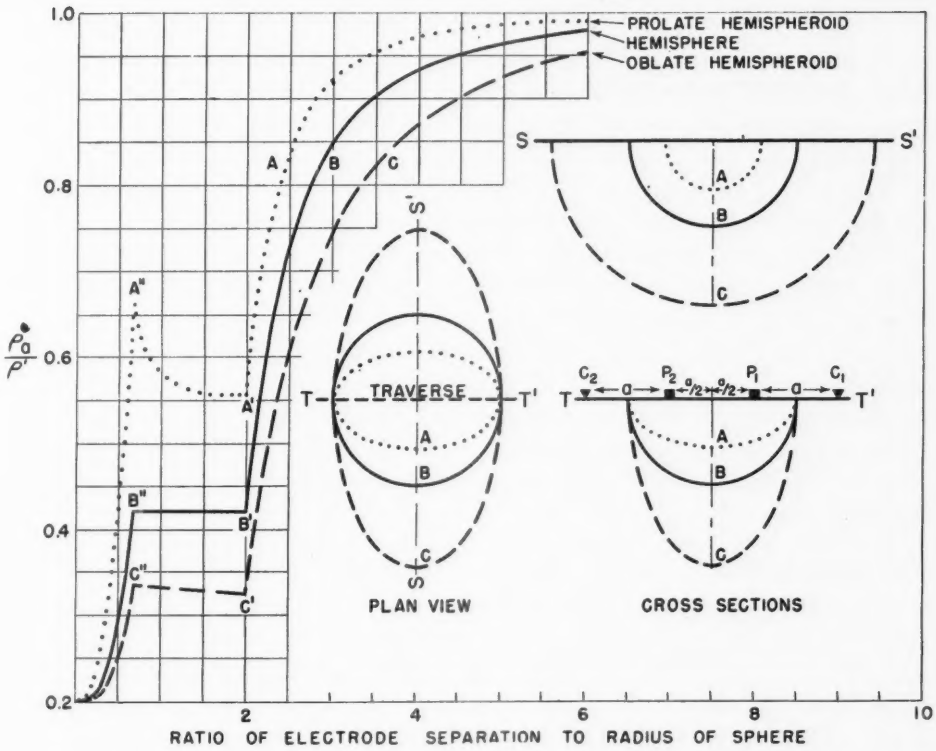


FIG. 10. Theoretical vertical resistivity profiles over hemispheroidal sinks. Profiles taken along traverse $TT'$ with center of configuration at center of hemispheroids. $\rho''/\rho' = \frac{1}{5}$.

$= 0.553 : 1.000 : 1.944$. The corresponding proportion of the volumes, which vary as the square of the radii, is $0.306 : 1.000 : 3.779$. The ratio of the resistivity of the material within the sink to the resistivity of the surrounding material is $1 : 5$.

For each of the vertical profiles, the center of the electrode configuration is maintained over the geometric center of the theoretical sink. Because of symmetry, it follows that both the Lee and Wenner configurations give the same theoretical vertical profile for a given sink.

The vertical profile curves display features that are helpful guides in the interpretation of the geology. For small electrode separations, the apparent resistivity is essentially equal to the resistivity of the material within the sink. In the present example, as the electrode configuration is expanded, the apparent resistivity becomes larger. The first breaks in the curves, at $A''$, $B''$, and $C''$ (Fig. 10), occur at the point where the current electrodes simultaneously cross the boundary of the sink. A sharp peak occurs at this point for the prolate hemispheroid only. As the electrode configuration is expanded further, each curve tends to form a plateau. These anomalous features of the curves are due to a converging current effect, which is best displayed by the prolate spheroid.

As the electrode configuration is expanded further, abrupt changes in slope at

$A'$, $B'$, and $C'$ (Fig. 10) occur at the point where the potential electrodes simultaneously cross the boundary of the sink. This abrupt change is apparently one of the most reliable interpretive features of the vertical profile; and it is very similar to that obtained for a vertical profile over a vertical fault as a potential electrode crosses the fault (Broughton Edge and Laby, 1931, p. 254).

Finally, for large electrode separations, the curves approach asymptotically the true resistivity value of the material surrounding the sink.

The vertical profile curves show that the vertical profile method is very sensitive to the margins of the sinks over a wide range of radii of revolution and indicate that the vertical profile method should, therefore, be a very valuable tool in outlining a filled sink. In spite of the large differences in volume of the theoretical sinks considered in this example, the general shapes of the curves are similar. For the dimensions and resistivity contrast used, the vertical profile is rather sensitive to variations in the depth of such sinks, that is, to the radii of revolution. The sensitivity manifests itself principally in the plateau part of the apparent resistivity curve.

*Theoretical Vertical Resistivity Profiles Over Hemispherical Sink*

Figure 11 shows the apparent resistivity values for vertical profiles taken on a set of traverses located at different distances from the center of a hemispherical sink. The resistivity contrast is the same as in the previous problem. For the single vertical profile taken on each traverse, the center of the configuration lies along a radial line perpendicular to the traverse and remains fixed as the configuration is expanded. Because of symmetry, the apparent resistivity values shown apply equally well to both the Lee and Wenner configurations. Except for the scale of plotting, the vertical profile for traverse 1 is comparable to curve $B$ given for the hemisphere in Figure 10.

For vertical profiles taken along traverses that intersect the sink, the apparent resistivity for small electrode separations is essentially equal to the true resistivity of the medium lying inside the sink. All such profiles show discontinuities in slope, the most pronounced discontinuity occurring at the point where the potential electrodes cross the boundary. The apparent resistivity values in the area of the most pronounced discontinuity in slope are nearly the same as the resistivity value constituting the horizontal plateau region $A'A''$ of curve 1 (Fig. 11).

For the traverse that is tangent to the hemispherical sink (curve 4, Fig. 11), the vertical profile starts for a very small electrode separation with an apparent resistivity value that is intermediate between the true resistivity of the material within the sink and that of the surrounding material. Further, for an expanding configuration this curve shows a continuous slope, a feature that characterizes the vertical profiles along traverses that do not intersect the sink.

For all vertical profiles taken outside the hemispherical sink, the apparent resistivity value for small electrode separations essentially equals the true resistivity of the medium outside the sink. For greater electrode separations, the

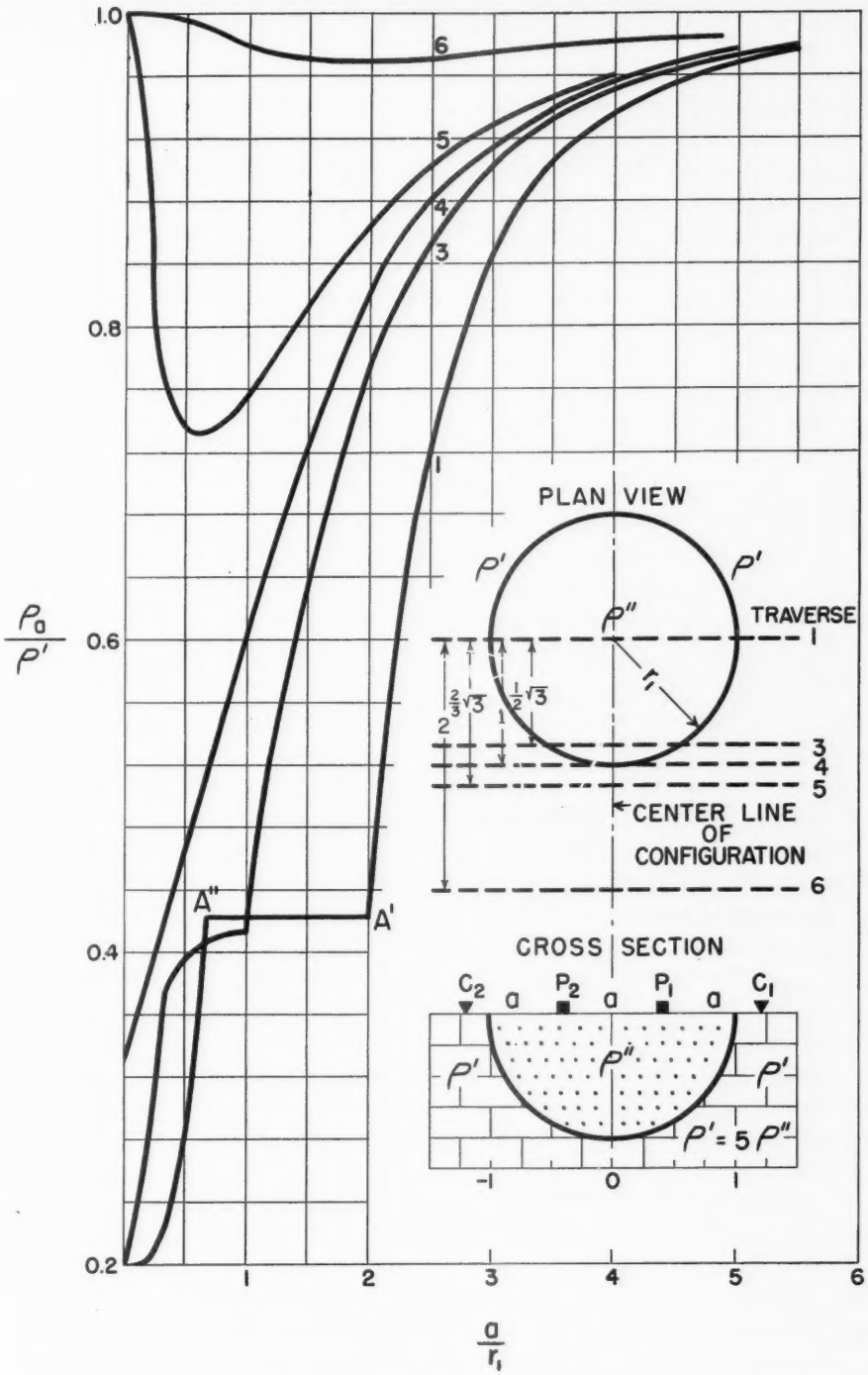


FIG. 11. Theoretical vertical resistivity profiles over hemispherical sink, with center of configuration at various distances from center of hemisphere.

apparent resistivity reaches a minimum value (curve 5, Fig. 11), the location of which shifts to the right for succeeding traverses more removed from the sink (curve 6, Fig. 11). For very large electrode separations, irrespective of whether the traverses transect the sink, the apparent resistivity approaches asymptotically the true resistivity value of the medium outside the sink. These features of the vertical profiles that pass tangent to or outside of the hemispherical sink can be explained qualitatively on the basis of the ratio of sink material to the total volume of earth within which the field of the current is appreciable.

The corresponding vertical profiles for prolate and oblate hemispheroids would not be identical with those for the hemispherical sink shown in Figure 11. However, the latter curves, together with those in Figure 10, can be used to determine qualitatively the general character of the former.

### DETECTABILITY OF HEMISPHERICAL SINK

It can be shown from the basic equations that for traverses outside of the sink the value of the electrode separation at the minimum of the curves in Figure 11 (curves 5 and 6) is independent of the resistivity contrast. On this basis an equation was established to give the apparent resistivity for the electrode separation at which the minimum occurs in curve 6 of Figure 11. It can be reasoned that the maximum resistivity anomaly for any Wenner horizontal traverse passing outside the hemisphere occurs when the center of the configuration is closest to the center of the sink. Therefore, since the curves in Figure 11 represent the apparent resistivity for various values of $a$ at this point of closest approach, they can be used to determine the anomaly index for Wenner horizontal profiles taken at various distances from the center of the sink. Table IV gives the anomaly indices for various resistivity contrasts when the value of the electrode separation is such that these indices are maximum in absolute value along a traverse that passes at a distance equal to the diameter of the sink from the center of the sink (traverse 6, Figure 11). This electrode separation is about equal to the diameter of the sink.

For the Lee configuration, the maximum resistivity anomaly is not found when the center of the configuration is closest to the center of the sink (see Fig. 4). However, since the Lee curves for horizontal traverses removed somewhat from the sink have maximum anomalies not greatly different from the Wenner maximum anomalies, the following discussion applies equally well to the Lee data.

For a given value of the electrode separation, there exists a distance from the hemispherical sink beyond which the sink cannot be detected. Also, there exists in any specific area, depending on the size of the sink and resistivity contrasts involved, a most desirable electrode separation as well as an optimum distance between traverses. Both of these factors can best be determined by a careful study of the curves in Figure 11 or from a similar set of curves corresponding to another known resistivity contrast.

When the usual irregularities or noise level of the resistivity readings in the

TABLE IV

ANOMALY INDICES OF WENNER HORIZONTAL PROFILES AT A DISTANCE FROM THE CENTER EQUAL TO THE DIAMETER OF THE HEMISPHERICAL SINK WITH OPTIMUM ELECTRODE SEPARATION
(Sign added to differentiate between maxima and minima)

| Sink | $k$‡ | Anomaly index* |
|---|---|---|
| Perfect conductor | −1.0 | −0.055 |
| Better conductor than country rock | −0.8 | −0.040 |
| | −0.667 | −0.032† |
| | −0.6 | −0.028 |
| | −0.4 | −0.017 |
| | −0.2 | −0.008 |
| Same conductivity as country rock | 0.0 | −0.000 |
| Poorer conductor than country rock | +0.2 | +0.007 |
| | +0.4 | +0.013 |
| | +0.6 | +0.019 |
| | +0.8 | +0.024 |
| Perfect insulator | +1.0 | +0.029 |

* Percent anomaly for traverses outside of sink is obtained by multiplying index number by 100.
† Corresponds to minimum in curve 6, Figure 11.
‡ $k=(\rho''-\rho)/(\rho''+\rho)$.

field are taken into account, the anomaly of curve 6 (Fig. 11) can scarcely be found. Thus, for the dimensions and resistivity contrast assumed, a traverse that passes a hemispherical filled sink at a distance from its center equal to or greater than its diameter will probably not show a recognizable anomaly. Since resistivity contrasts above 5 to 1 fail to make an appreciable increase in the anomaly in such cases, this general rule is valid even for greater resistivity contrasts. Table IV shows that for a traverse taken at a distance from the center of the sink equal to the diameter of the sink, the anomaly is only 5.5 percent of the regional resistivity value in the case of a perfect conductor and 2.9 percent in the case of a perfect insulator. If the noise level is of this order of magnitude, a hemispherical sink could be missed, even where there are large resistivity contrasts, when successive traverses are spaced as far apart as a distance that equals twice the diameter of the sink.

As a general rule the spacing of successive reconnaissance horizontal profiles should be made approximately equal to the diameter of the expected sink (or the average diameter if the plan of the sink is irregular). This conservative rule can be relaxed in some areas so that the traverses can be spaced with safety at a distance that equals approximately three times the radius of the sink. A traverse spacing of twice the diameter is regarded as unsafe because a sink could be missed. As implied above, in order for an anomaly to be observed on at least two adjacent traverses in horizontal profiling, the traverses must be spaced no farther apart than the diameter of the expected sink.

In order to determine the optimum electrode separation to be used along re-

connaissance horizontal profiles in a given area, one must compromise between small separations that give better definition across the boundary of the sink and large separations that permit detectability of the sink at greater distances from the sink. As a general rule, the electrode separation $a$ should be made approximately equal to the radius (or one-half the average diameter if the plan of the sink is irregular) of the expected sink. This conservative rule can be relaxed in some areas so that a larger electrode separation may be safely, and perhaps advantageously, used. However, it should be cautioned that as the electrode separation is increased above an optimum amount, the value of the apparent resistivity within the sink increases rapidly. When using this rule, station intervals of $a/2$ or less are recommended for either the Lee or Wenner configuration.

## CONCLUSIONS

Several conclusions and implications have resulted from our study of the various types of resistivity data obtained in the vicinity of a sink filled with a material whose resistivity is less than the resistivity of the country rock.[4]

Over a hemispheroidal or hemispherical sink, the resistivity profiles using the Lee partitioning method give more diagnostic information than the resistivity profiles using the Wenner configuration and are usually well worth the additional time, equipment, and personnel required to obtain them. Moreover, the horizontal profiles provide a clearer picture than the corresponding vertical profiles. It is not to be concluded, however, that the Lee horizontal profiles should be used to the complete exclusion of other techniques. On the contrary, in the search for filled sinks we believe (1) that each technique has its rightful place, and (2) that the most effective resistivity survey is made by combining judiciously the various field techniques proposed herewith.

To discover a filled sink in an area of moderate or high resistivity contrast, a reconnaissance survey is first made. For the reconnaissance traverses, the horizontal profiling technique is preferred because of the rapidity and low cost of coverage. The electrode separation in this survey should approximately equal the average radius of the sinks that are expected to be found in the area, and the station interval should equal half the electrode separation. To avoid missing a sink, the distance between parallel reconnaissance traverses should preferably be less than twice the diameter of an expected hemispherical sink or less than twice the average diameter of an expected irregularly shaped sink. A convenient safe rule is to make the distance between traverses approximately equal to the diameter of an expected hemispherical sink or the average diameter of an expected irregularly shaped sink. Depending on several local factors, such as resistivity contrasts, expected thickness of the filled sink, noise level, and other operational factors, some flexibility in this rule is permissible.

As the reconnaissance work progresses, the compilation of appropriate hori-

[4] Many of these conclusions and recommendations were the basis for further field studies in the summer of 1953 (Cook, 1954).

zontal profile curves should be kept up to date and used to guide the additional, detailed work warranted in areas of low resistivity that indicate the likelihood of filled sinks. An equi-resistivity map, whose compilation should also be kept current, presents an overall picture of the progress of the survey and facilitates the interpretation especially with regard to the proper choice of promising areas for detailed surveying.

The detailed work over the sink can be done in one or more ways. To outline the horizontal extent of the sink most accurately, Lee horizontal profiles that radiate out in various azimuths from the center of the sink are probably preferable. In this detailed horizontal profiling, a better approximation of the size of the sink is available and, therefore, the electrode separation should be chosen to reflect the expected diameter of each sink separately as indicated in the rules given above. To obtain a rough estimate of the thickness of the sink, vertical profiles using the Lee configuration along these same radial traverses, with the center of the configuration as near as possible to the center of the sink, are preferred.

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GEOPHYSICS, VOL. XIX, NO. 4 (OCTOBER, 1954), PP. 791–801, 11 FIGS.

# GEOPHYSICAL HISTORY OF THE GOOD FIELD, BORDEN COUNTY, TEXAS*

HOLLAND C. McCARVER†

## ABSTRACT

The Good oil field, located in the southwestern part of Borden County, Texas, became a reef oil producer in April, 1949. The discovery well was drilled subsequent to a seismic program along a suspected reef trend. The discovery was made without benefit of reef reflections, and was based only on maps showing Permian draping. This technique offers interesting comparisons between seismic and subsurface data.

## INTRODUCTION

The Good oil field was one of the first West Texas Pennsylvanian reef fields that was deliberately looked for and discovered as such. Each step in its exploration history was specifically designed to find a productive reef within a rather limited area utilizing a particular exploration idea. That a reef discovery resulted is to some extent due to luck, but the early recognition of a trend, a specific objective, and an exploration technique should receive the major share of the credit.

## LOCATION

As shown in Figure 1, the Good field is located in the southwestern part of Borden County, Texas, approximately 30 miles northwest of Big Spring and 20 miles southeast of Lamesa. Geologically, it lies at the southwest end of the arcuate Scurry-Reinecke-Vealmoor reef trend.

## HISTORY OF DISCOVERY

### *Early History*

The Good Ranch area first attracted the attention of the Seaboard Oil Company early in 1948. The Pennsylvanian reef masses at Spraberry Deep and at Vealmoor had just been discovered, and the Good ranch lay in possible "reef country" between these two features. Also, the ranch appeared to be located in an area known to be regionally high on the Yates sand.

At the time of this initial interest, however, the Good Ranch was under lease to the Condor Petroleum Company. Pan American Production Company and Seaboard Oil Company jointly entered into negotiations with Condor and in June, 1948 obtained the ranch acreage; the original lessee retained the southeast quarter of each section. Pan American and Seaboard immediately started exploration activity, with Seaboard as the operator.

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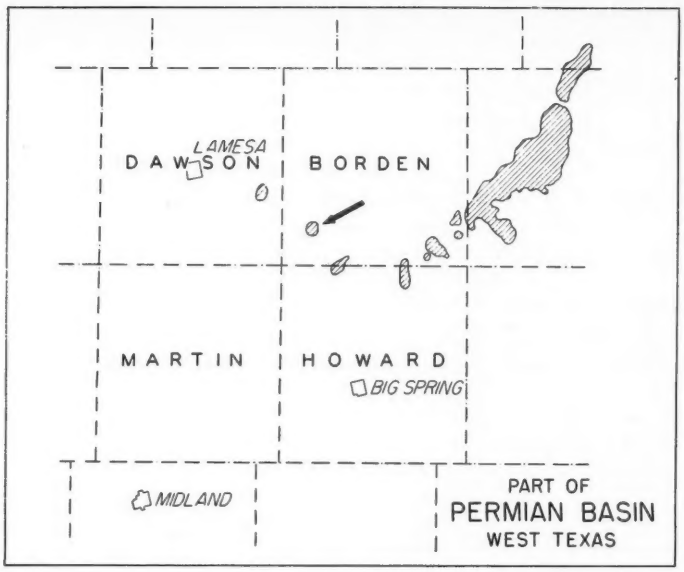


FIG. 1. Map of portion of the Midland Basin of West Texas showing the location of the Good field.

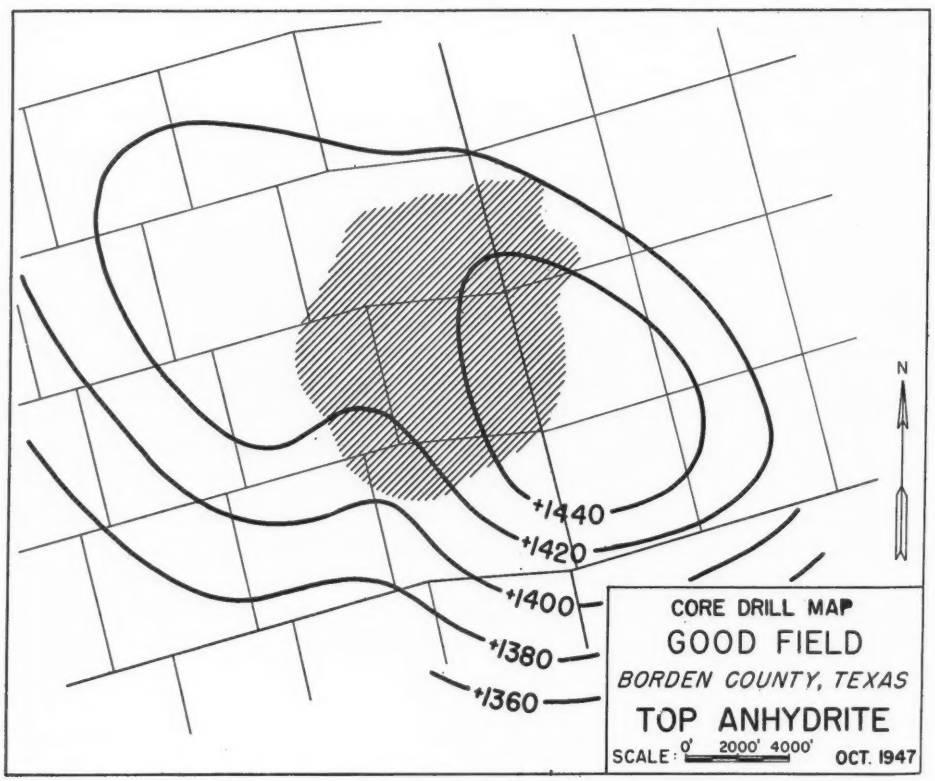


FIG. 2. Core drill map of the Good field area contoured on the anhydrite. The productive reef area is shaded.

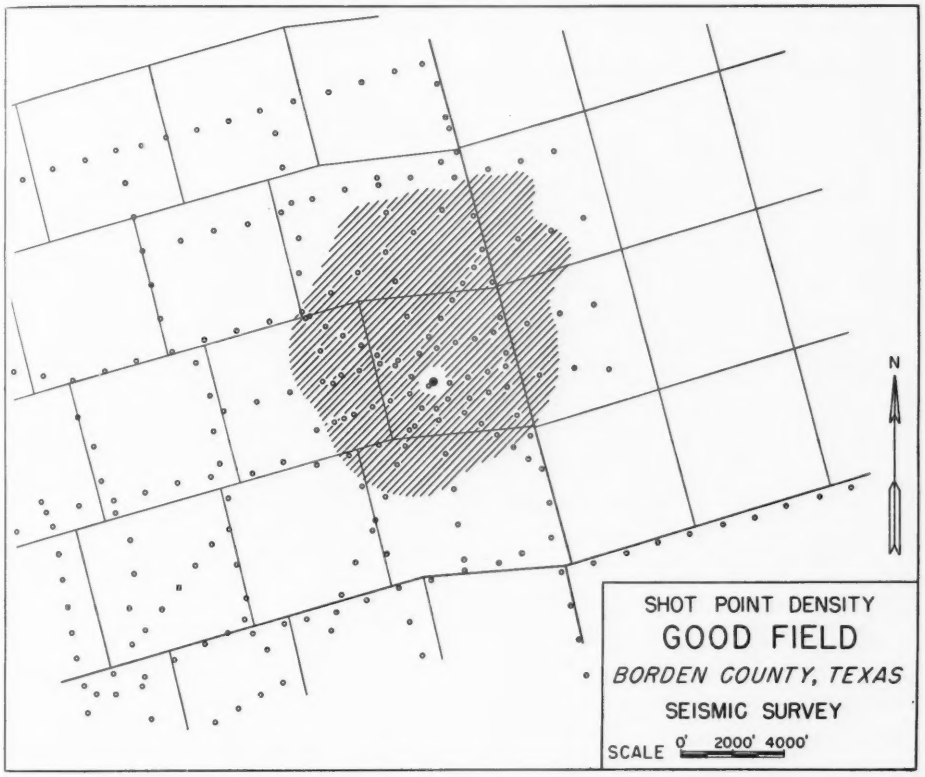


FIG. 3. Map showing shot point density in Good field area.

Study was first made of a core drill map furnished by Mr. Ellis Hall of Condor Petroleum Company. This map, an interpretation by Mr. R. G. Maxwell of core drill points on top of the anhydrite, indicated a possible high area in the northeastern part of the ranch. The actual value of this core drill map was unknown at the time, but as seen from Figure 2, the 1,420-foot contour on the anhydrite approximately encircled the present day limits of reef production. The apex of the core drill high, however, was centered some 2,000 feet southeast of the edge of the field.

*Seismic Survey*

In August, 1948 Seaboard moved a Seismic Engineering Company crew to the Good ranch and began seismic profiling. This party, under the direction of Mr. C. C. Williams, began shooting a two-mile-by-two-mile grid design to cover the entire ranch with a moderately detailed program. Most of this seismic survey utilized a 1,320-0-1,320 ft split-continuous spread, with a few 1,000-ft and 750-ft spreads in local areas requiring close detail work. Shot hole depths averaged 115 ft and the average dynamite charge was seventeen pounds. The survey was

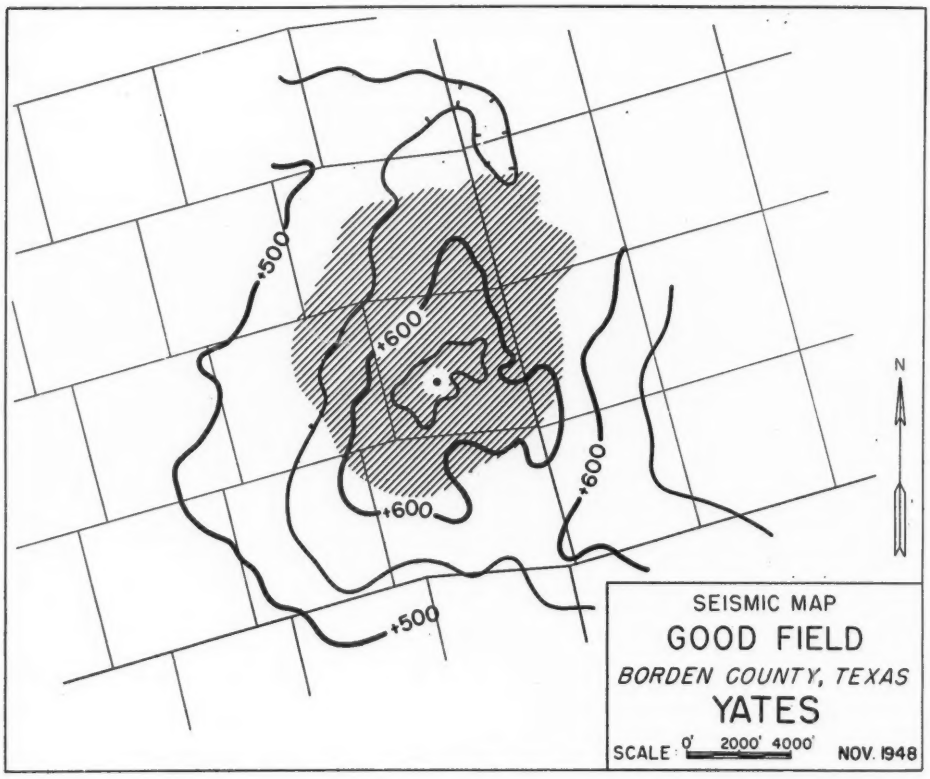


FIG. 4a. Reflection seismograph map of Good field contoured on the Yates horizon. Contour interval is 50 feet.

made with a twenty-trace recording unit, two seismometers being used with each trace. Data were adjusted to a reference plane by using uphole times and an 8,000-ft/sec reference velocity.

Reflection energy was readily obtained from numerous horizons to a depth of approximately 6,000 ft, with the outstanding events assumed to be the Yates and the top of the Spraberry. No persistent reflections were recorded below the base of the Permian section, and no event was ever identified as a reef reflection.

As early as the twentieth shotpoint, the seismic survey pointed to the northeast portion of the ranch as an area of interest, and additional profiling conclusively indicated the presence of an anomaly. As can be seen in Figure 3, shotpoint density on the anomaly was approximately 35 per square mile.

Seismic data covering a considerable range of depths were carried on the cross-sections plotted along each profile shot, but structural maps were prepared only for the Yates and Spraberry horizons. The Yates seismic map, shown in Figure 4a, indicated a positive, low-relief feature with a maximum closure of approximately 75 feet. This anomaly coincides generally with the one shown by the earlier core drill work.

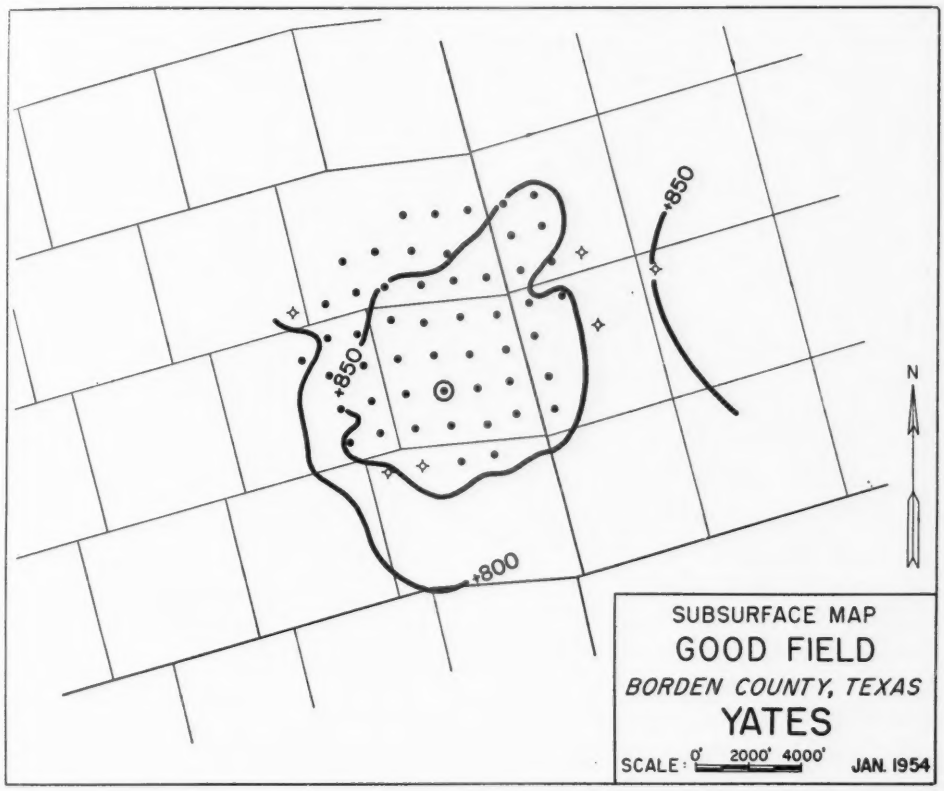


FIG. 4b. Subsurface map contoured on the Yates horizon. The discovery well is circled.

Figure 5a shows the Spraberry seismic map. The Spraberry anomaly conforms with the shallower features, but seismic closure increases to approximately 125 feet.

From experience gained at the Spraberry Deep field and the Vealmoor field, Seaboard had reason to believe that the seismic anomaly mapped was a Permian "structure" caused by differential compaction and draping over a reef mass. To check this reasoning, the Pan American-Seaboard No. 1 Good was located at the position indicated in Figure 4a. This well encountered reef limestone at 7,900 feet and in April, 1949 it was completed for 448 barrels of oil per day through a $\frac{1}{4}$-inch tubing choke.

*Seismic and Subsurface Comparisons*

The Good field is now developed to the extent that comparisons can be made between the seismic and subsurface maps.

The Yates seismic map, Figure 4a, and the Yates subsurface map, shown in Figure 4b, show excellent conformity. The subsurface contour interpretation is smoother than the seismic, and the maximum closure is slightly less.

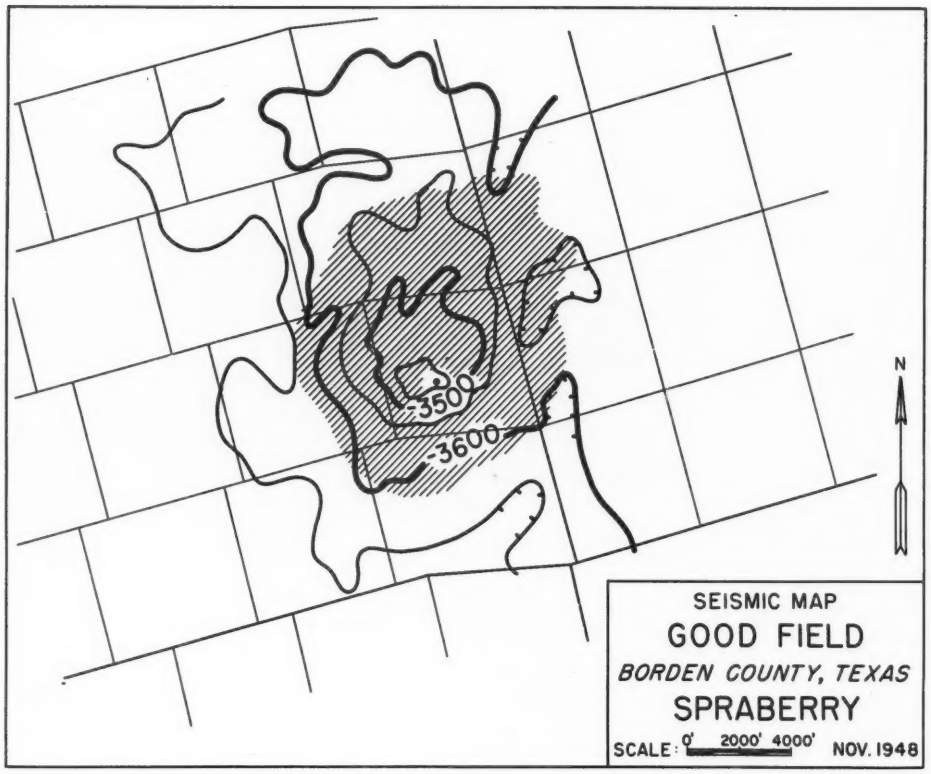


FIG. 5a. Reflection seismograph map contoured on the approximate top of the Spraberry horizon. The location of the discovery well is shown, and the shaded area covers the productive limits of the field.

At the Spraberry level, similar comparisons can be made between the seismic map in Figure 5a and the subsurface map in Figure 5b. The highest point on the subsurface map, however, has shifted about one well location north of the highest seismic point.

Below the Spraberry level, only erratic and discontinuous reflected events were recorded, and no maps could be made on reef or pre-reef horizons. Occasional strong dips did support the shallower structural interpretations, however, and gave indications of possible increase in structural closure at depth.

Figure 6 shows a map contoured on top of the reef. Although over 400 ft of reef "structure" or "build-up" is mapped, no indication of a feature of this magnitude could be seen in the seismic data. Several of the seismic lines roughly parallel well profiles, but painstaking study could not produce bona fide seismic reef correlations, even when using reef well tops for a guide.

Figure 7 is a composite east-west cross-section showing a comparison of seismic and subsurface information. Location of this section is shown in Figure 5b. As indicated, there is good cross-section conformity at the Spraberry level,

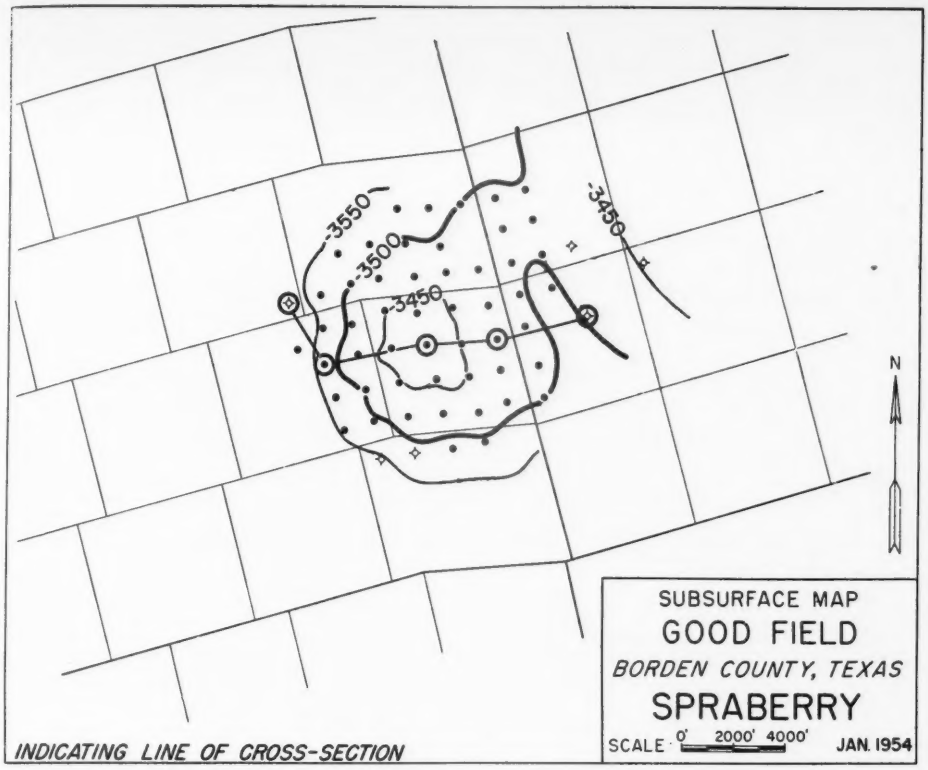


FIG. 5b. Subsurface map contoured on the top of the Spraberry sand section. Contour interval is 50 feet.

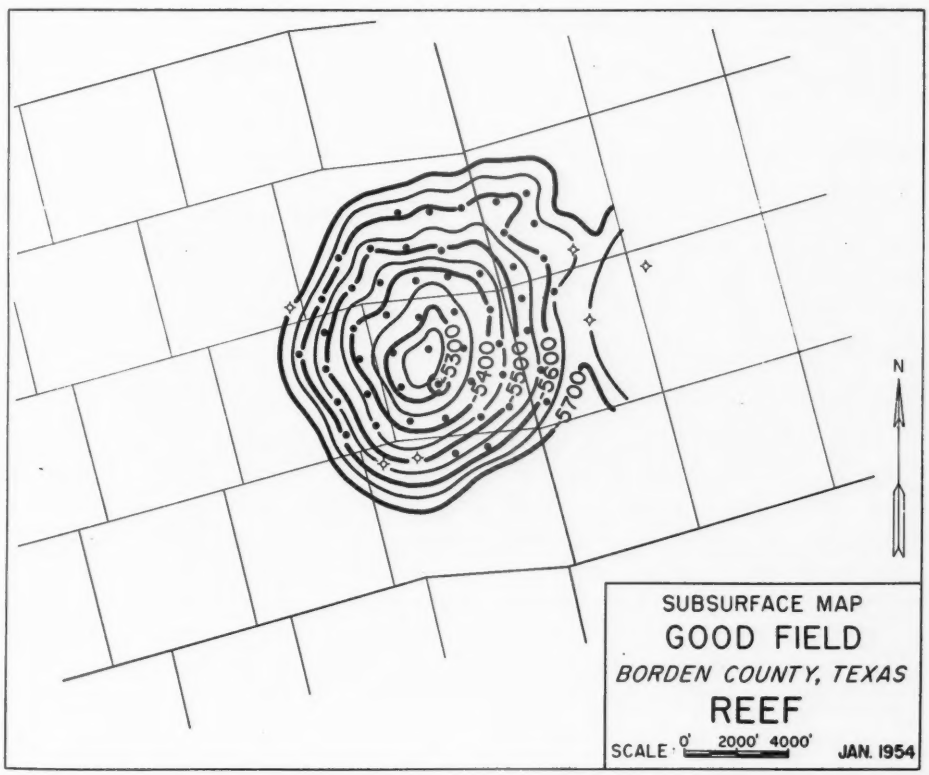


FIG. 6. Subsurface map showing contours on top of the Pennsylvanian reef limestone. The two dry holes in the southern portion of the field found the reef hard, tight, and non-productive.

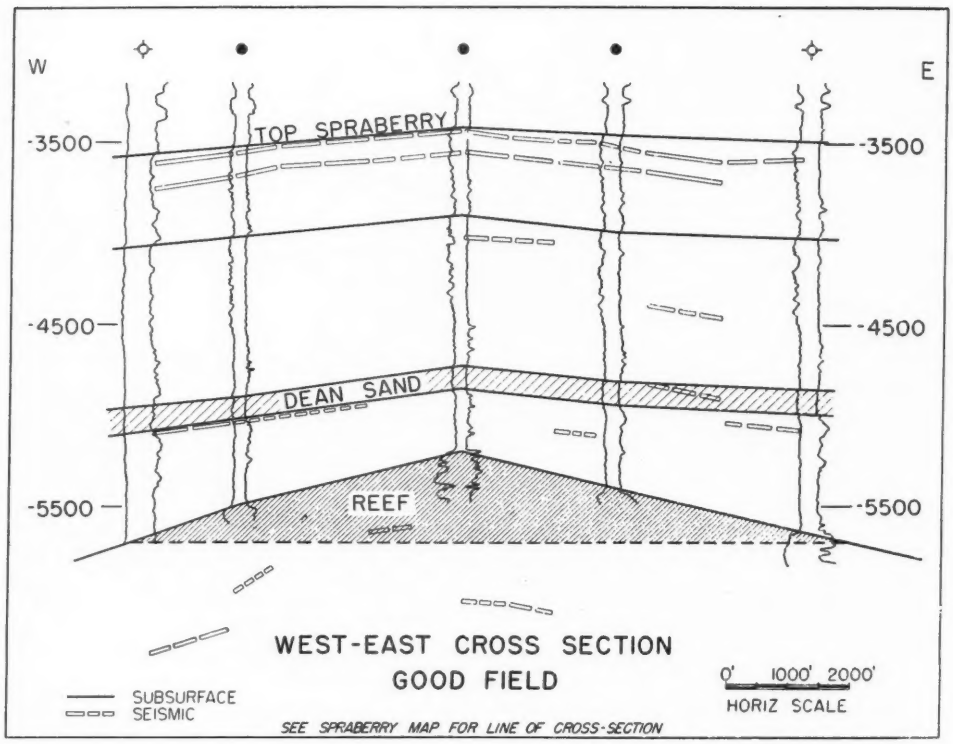


FIG. 7. West-east cross-section of the Good field showing the relationship of seismograph to subsurface data.

segmental conformity at the Dean sand horizon, and only poor and scattered dip comparisons at and below the reef level.

The seismic evaluation of the Good "reef structure," then, was almost entirely dependent on the ability to map structural draping in the Permian section. Since such low relief features *outside* of a reef trend could mean very little, close cooperation between the geologist and the geophysicist in seismic program planning was of great importance.

*Other Exploration Methods*

Early and generalized gravity studies in the West Texas reef province revealed a possible relationship between large gravity maxima and reef-building areas. This possible comparison received some support when the Good field, as well as Spraberry Deep and Vealmoor, appeared to be at least geographically related to the large gravity maxima shown on the Brown Geophysical Company map in Figure 8. Since, however, the Good field fell in a steep gradient area on the flank of this feature it was evident that a more detailed survey was necessary if gravity support for reefing or Permian draping was to be obtained.

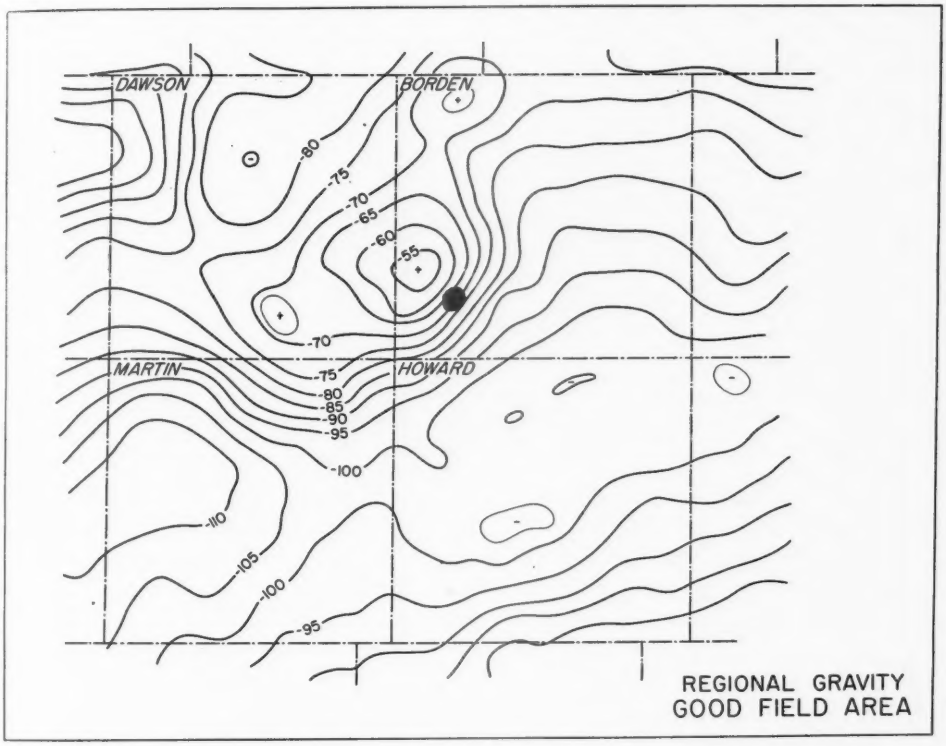


FIG. 8. A portion of the Brown Geophysical Company's regional gravity map of West Texas showing the location of the Good field. Contour interval is 5.0 mg.

A portion of the detailed gravity meter survey, which was conducted by Robert H. Ray Company, is shown in Figure 9. This map was contoured on observed data at one miligal intervals. The steep southeast gradient shown was only slightly disturbed by a minute minimum curve of the contours near the producing area.

Figure 10 shows some residual minima interpreted from these changes in contour regularity. At first glance, these minima appeared to be possible gravity "yardsticks" that could be used in reef exploration. Unfortunately, however, some 23 of these residual minima were mapped in the Good-Vealmoor area and 21 of them had no structural or seismic confirmation. This rather nebulous result prescribed a limited use of the gravity meter for reef exploration in the Good field area. Figure 11 shows the station density used in the detailed gravity survey.

*Production History*

As of January 1953, the Good field consisted of 49 producing wells. The maximum amount of reef pay above water was 486 feet, the average thickness being

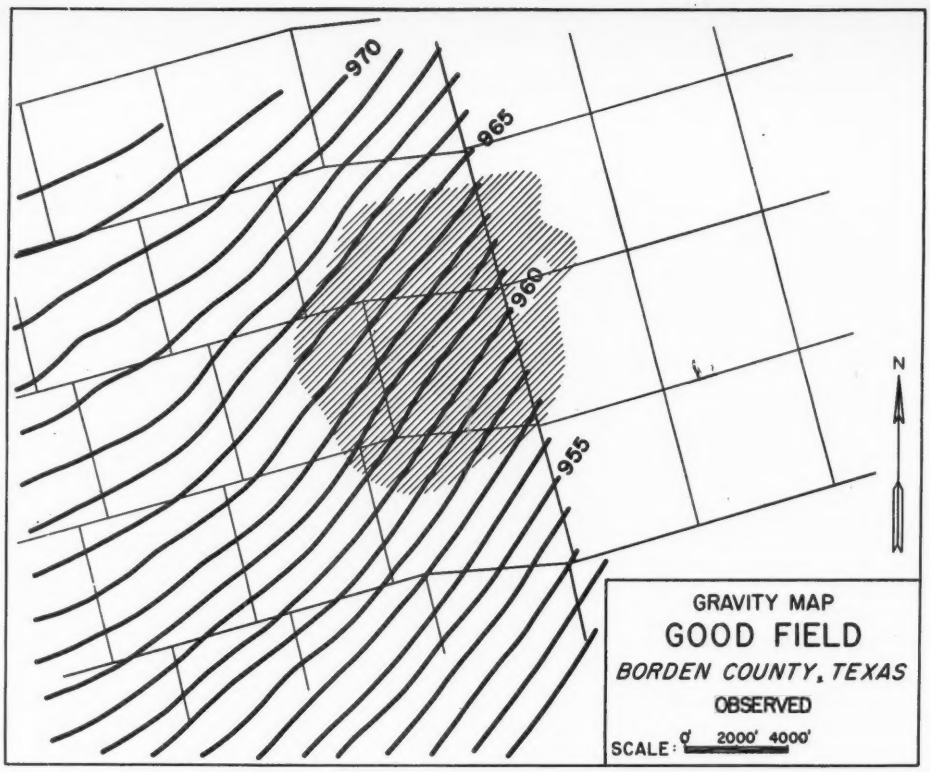


FIG. 9. Portion of a detailed gravity map of the Good field area. The observed data shown has a contour interval of 1.0 mg. The productive area is shaded.

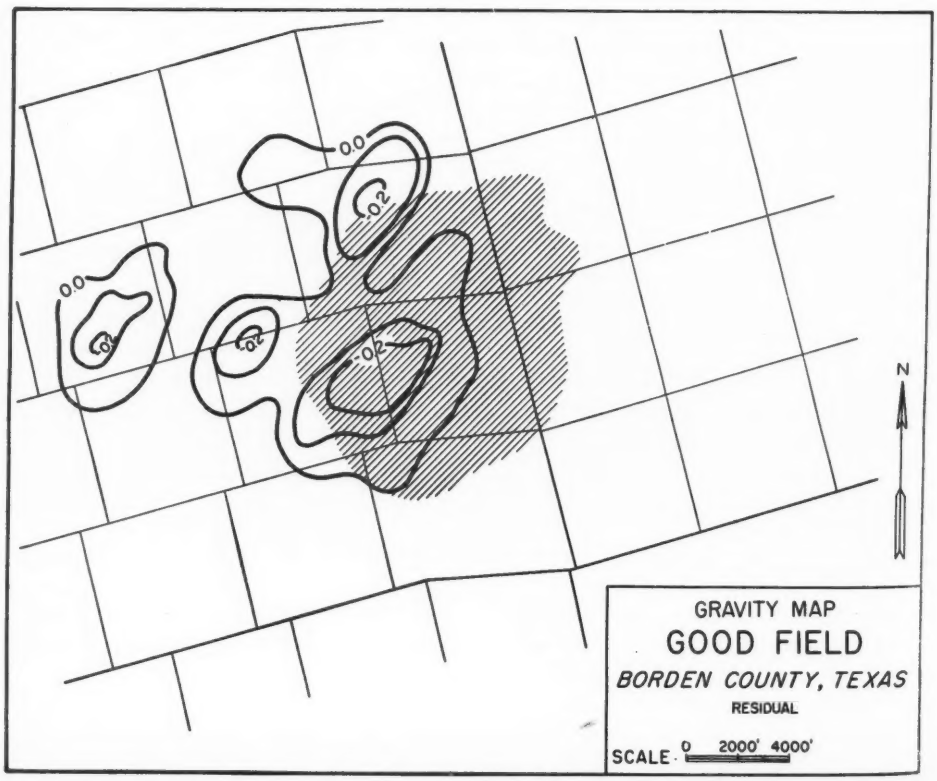


FIG. 10. A residual gravity map of the Good field area. The contour interval is 0.1 mg.

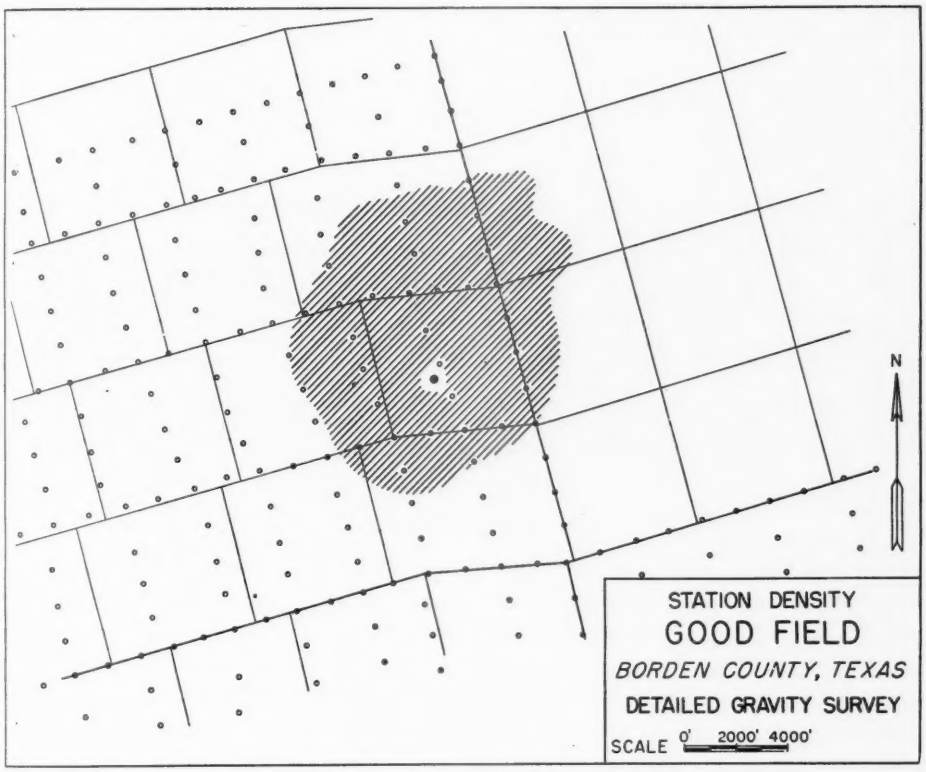


FIG. 11. A map showing the station density of the detailed gravity survey.

246 feet per well. The accumulative production through 1953 was approximately seven million barrels.

## CONCLUSIONS

Pennsylvanian reef masses, particularly of the Good field bioherm type, can be successfully mapped with the seismograph. Almost no reflections are obtained from the reef itself, but the presence of such a feature can be recognized from mappable structural draping in the Permian section. Detailed seismic work and joint geological-geophysical program planning in probable "reef country" are essential to the success of such a survey.

## ACKNOWLEDGMENTS

The writer wishes to thank the managements of the Condor Petroleum Company, the Pan American Production Company, and the Seaboard Oil Company of Delaware for permission to publish this paper.

GEOPHYSICS, VOL. XIX, NO. 4 (OCTOBER, 1954), PP. 802–819, 13 FIGS.

# PERFORMANCE OF RESONANT SEISMOMETERS*

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## ABSTRACT

A group of resonant vertical seismometers, each tuned to cover a part of the spectrum of microseism frequencies, has been operated for about one year.

These instruments (a) clearly distinguish between simultaneous microseisms from two separate sources; (b) show an improved signal-to-noise ratio for microseisms from a single storm, permitting earlier detection of storm onsets; (c) show clearly the increase in period of frontal microseisms as cold fronts move seaward from the east coast of North America; (d) record only the envelope of the oscillations, which greatly facilitates measurement of intensity as a function of time; and (e) appear to be very useful tools in continued attempts at hurricane location by means of microseism amplitude studies.

The performance of the instruments is demonstrated by seven case histories in which microseismic readings of seismometers tuned to different frequencies are related to the meteorological conditions which are apparently responsible for the microseismic activity.

## INSTRUMENTATION

The resonant seismographs used in this study consisted of highly underdamped vertical seismometers coupled through a large series resistance to critically damped galvanometers. The seismometers incorporate a design originally suggested by Lacoste (1934) for the use of zero length springs. Damping of the seismometers and over-all sensitivity were controlled by selecting appropriate values for the transducer coil impedance and the series resistance. Leeds-Northrup type 2,500F galvanometers ($T_g = 12$–$15$ sec) were used.

Figure 1 shows the steady-state magnification curves for the resonant seismographs. It is seen that each instrument is sharply tuned to a narrow band and that the peak magnification is roughly ten or twenty times greater at these periods than in conventional seismographs. Damping constants for the seismometers are given in Table I.

The magnification curves in Figure 1 are valid only for steady state sinusoidal ground motion. It is well known that microseism amplitudes often change rapidly, a typical variation taking the form of groups containing 3–8 oscillations. Without going into the details we may conclude from the results of Wilson (1932) that the response of tuned seismometers to typical microseisms consists of forced oscillations having the microseism period and slightly damped free oscillations having the period of the seismometer. The amplitude of the forced vibrations is roughly dependent on the magnification curves of Figure 1, whereas the free vibration amplitudes depend on the amplitude of the spectral components of the transient microseismic activity having periods near that of the seismometer. From comparison of tuned and standard seismograph records, we have found that forced

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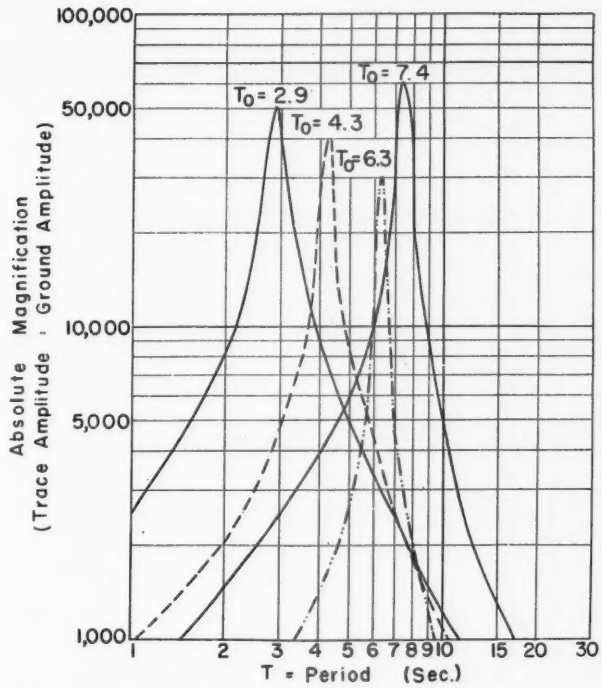


FIG. 1. Characteristic curves for four resonant seismographs, showing steady-state magnification as function of period.

vibrations account for the significant amplitude variations of the tuned seismographs and that these are directly related to period and amplitude changes of microseisms.

TABLE I

| Seismometer Period | Seismometer Damping Constant |
|---|---|
| 2.9 sec | 0.135 $sec^{-1}$ |
| 4.3 | 0.058 |
| 6.3 | 0.019 |
| 7.4 | 0.029 |

## PERFORMANCE

The performance of the new instruments can be shown best by a series of case histories of different microseismic situations. Conventional seismograms are presented for comparison in many of the cases to be described.

*November 3–4, 1952*

The weather chart (lower right) in Figure 2 shows a weak cold front just east of Palisades (*P*) at the time indicated. The dotted line off the east coast on this

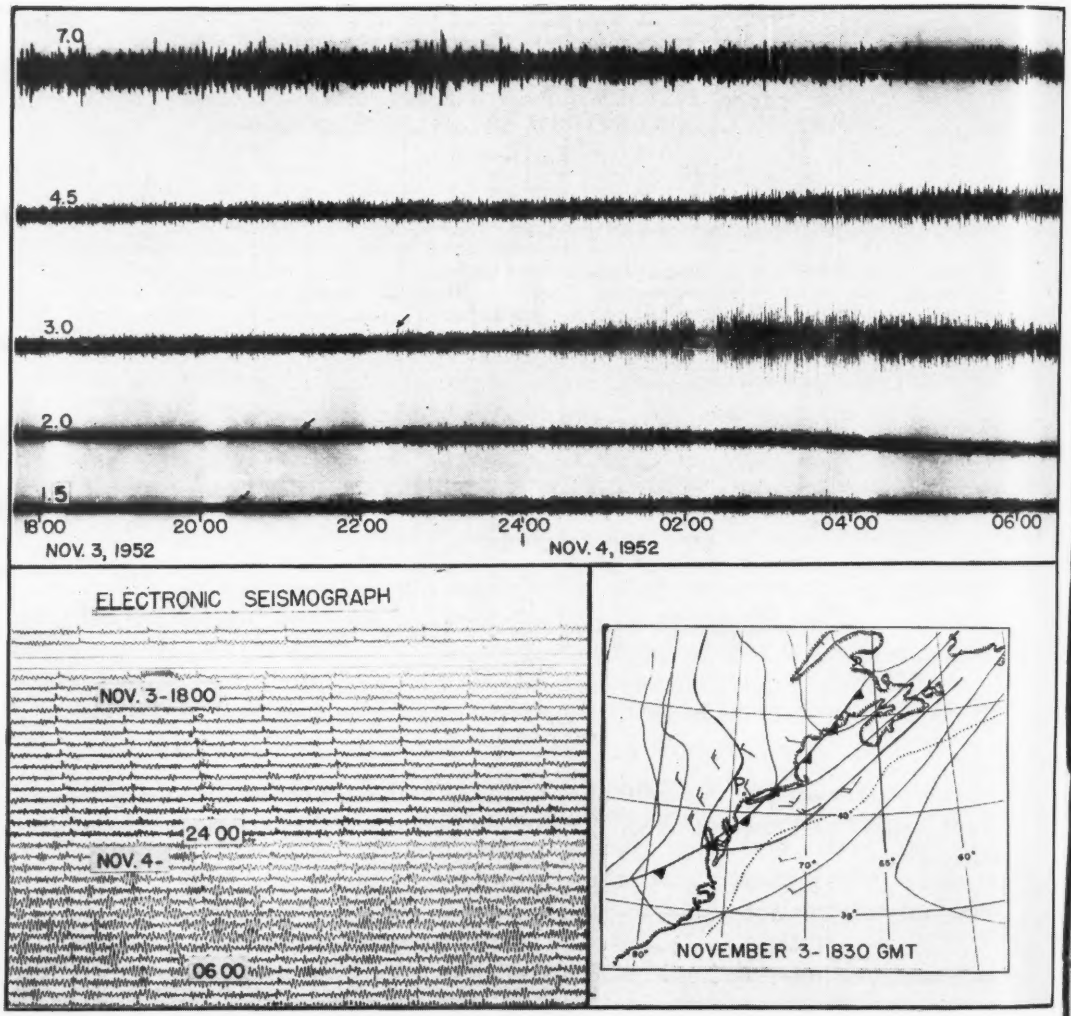


FIG. 2. Microseismic effect at Palisades of weak cold front of November 3–4, 1952. Record from resonant seismographs at top, from electronic seismograph at lower left.

and subsequent charts represents the 1,000-fm depth contour. The record of an electronic seismograph is shown to the left of the map. This instrument is usually the most sensitive of the Palisades seismographs to short-period microseisms. The earliest detectable microseism signal on this trace occurs about 2230, November 3, with no strong intensity until after 2400. Maximum intensity on this record is from 0100 to 0600, November 4, the measured period being about 3 sec.

The upper part of Figure 2 reproduces portions of the resonant seismograms having $T_0$ set, respectively, at 1.5, 2.0, 3.0, 4.5 and 7.0 sec. Each band has a duration of 13 hours. The intensity of the recording light spot is decreased for 15

minutes every two hours. Owing to the slow drum speed, traces from five seismograms can be recorded on a single drum as shown. Further, the amplitude envelope for a particular frequency can be seen readily, without laborious measurement. The bristle or brush effect results from the compressed time scale and is the signature of the microseism wave groups frequently observed on the faster speed records. Since the brush patterns are not usually simultaneous on the several channels, it follows that different signals are being recorded on the respective channels, the difference being essentially one of period.

The resonant seismograms show a succession of events from the 1.5- to the 4.5-sec bands, beginning on the former about 2030, November 3, and corresponding in time to the offshore movement of the cold front. Thus, the microseism signal on both the 1.5 and 2.0 sec bands precedes significant activity on the short period electronic seismograph. The maximum intensity is observed on the 3.0 sec channel at the time when the signals, having a period of three seconds, showed maximum intensity on the electronic record. The calibration curve for the electronic seismograph shows peak response of 10,000 at 1.7 sec. This suggests that the initial 1.5- to 2.0-sec microseism signal was very weak and that the resonant seismograph is more efficient in detecting such signals when close to the resonant frequency of the instrument. A definite difference in response occurs for microseisms with periods $\frac{1}{4}$ to $\frac{1}{2}$ octave apart. The increase in microseism period with time and increasing frontal distance (and water depth) is clearly shown by the lower four resonant seismograms.

It is noteworthy that the high noise level on the 7.0-sec band does not affect shorter period channels and is not recorded on the electronic record, which still has a magnification of about 2,000 at 7.0 sec.

*October 6–8, 1952*

Charts A to D in Figure 3 show the progress of adjacent marine and coastal weather events from the middle Atlantic states to Greenland for October 6 to 8, 1952. Charts A and B show a steep pressure gradient over the ocean area between Labrador and Greenland. This gradient and related high winds weakened considerably during the latter part of October 7. Concurrently, a slowly-moving cold front approached the coast and then passed seaward, crossing coastal waters near Palisades (*P*) by 1230, October 7.

Resonant seismograms ($T_0 = 1.5$, 2.0, 3.0, 4.5 and 6.6 sec) from October 6 at 0900 to October 8 at 1300 are shown in Figure 4. A fairly strong signal is evident on the 4.5 and 6.6 sec bands of the October 6–7 records (upper set). This activity decreases considerably on the lower set of 4.5- to 6.6-sec records for the October 7–8 interval. During the more intense activity on October 6–7, the lines of maximum deflection (giving the brush effect) generally match on the 4.5- and 6.6-sec bands, indicating response to the same signal. This is supported by the fact that the measured period on the electronic seismogram for the dominant microseisms during this interval was 5 to 6 sec, or about midway between these resonant fre-

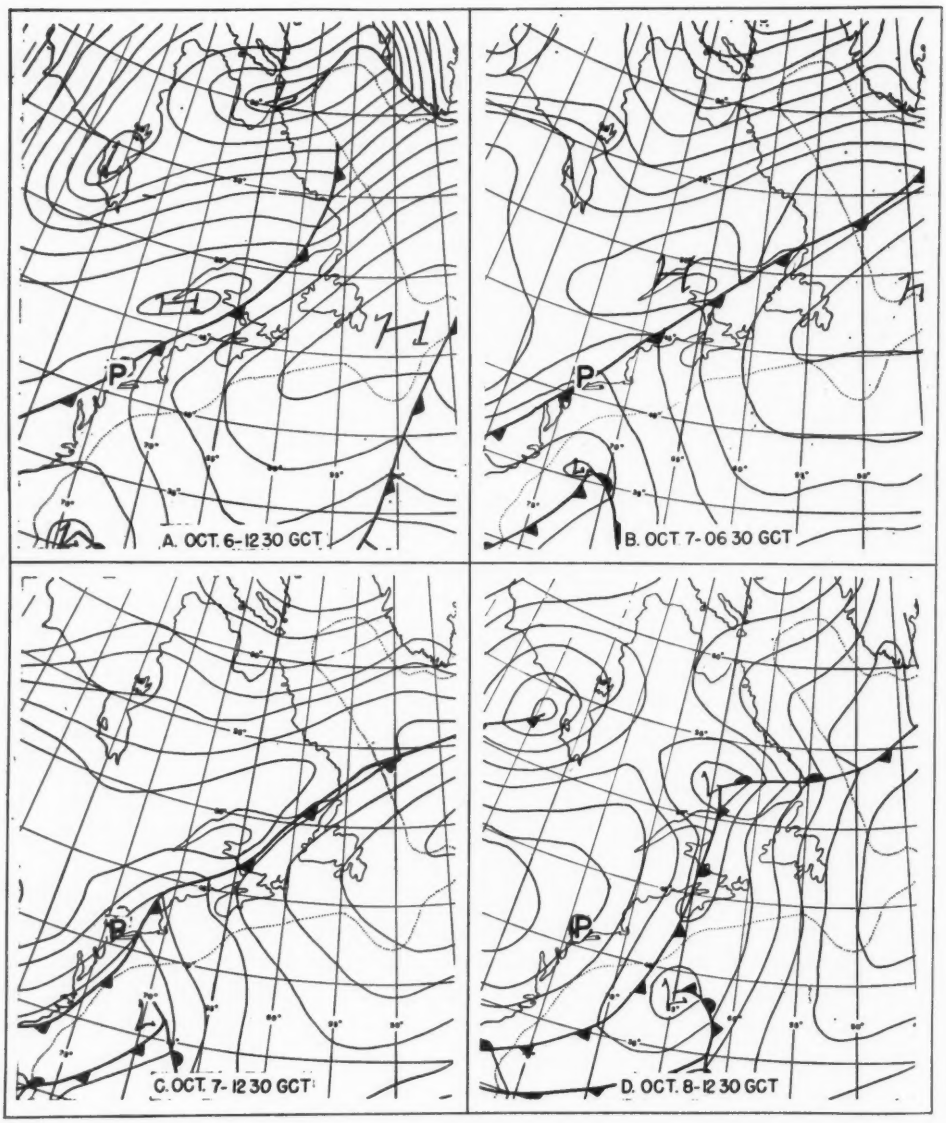


FIG. 3. Weather maps showing progress of weather events over Northwest Atlantic Ocean and adjacent land areas from October 6–8, 1952.

quencies. This long period microseism activity correlates well with the steep pressure gradient over waters east of Labrador and is a frequent occurrence with this weather pattern. The long period microseisms decreased in intensity as the pressure gradient weakened.

The three short period channels (1.5, 2.0, and 3.0 sec) on the lower set of

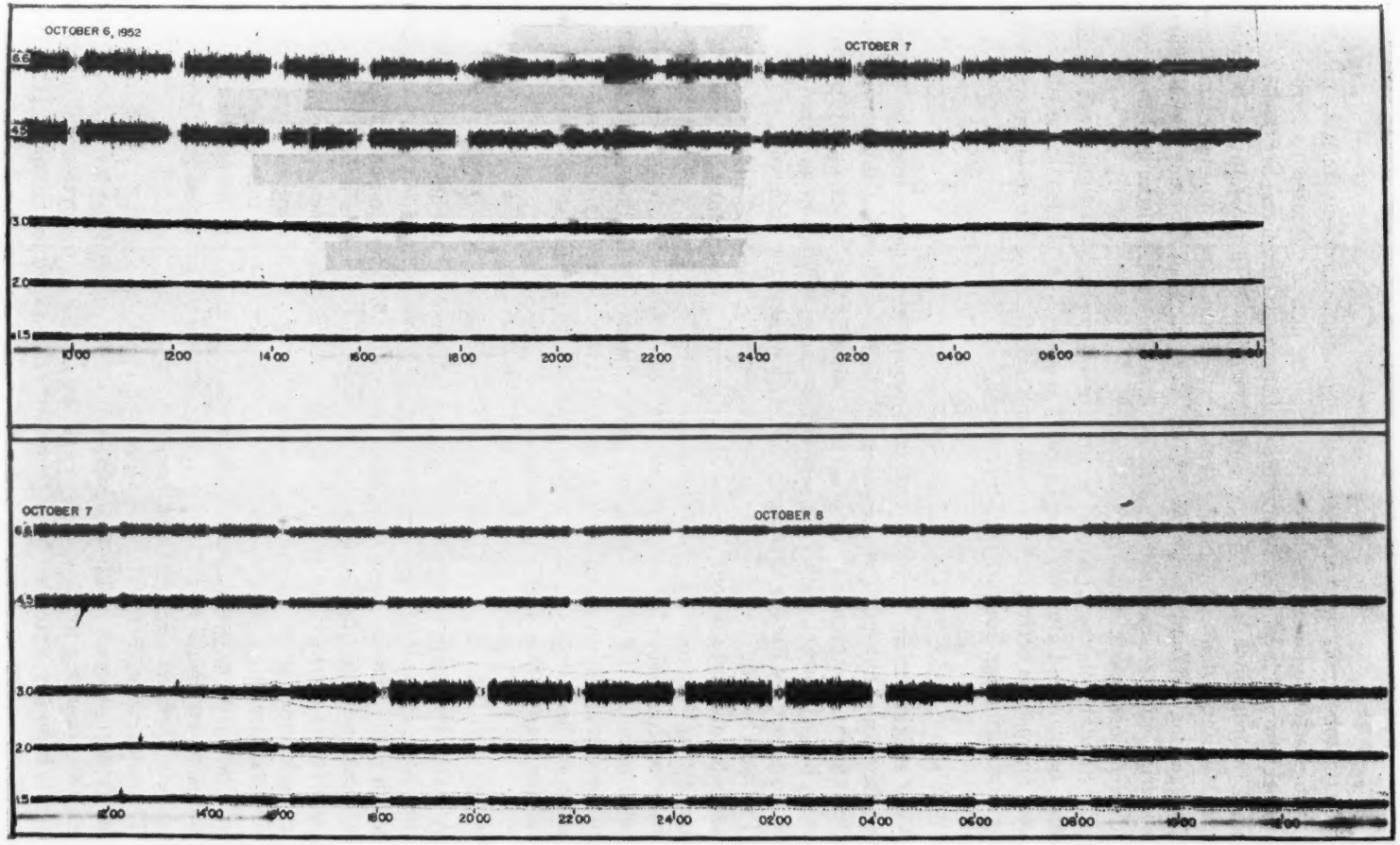


FIG. 4. Resonant seismograph records from Palisades covering period represented on weather maps of Figure 3.

records (October 7–8) show a sequence of increasing microseism activity proceeding from shorter to longer periods, while the long period microseisms were declining to background level. The amplitude envelopes (dotted lines) are based on the original records since lines of maximum deflection were too faint to be reproduced. Maximum deflections on the short-period bands are not usually simultaneous, suggesting different origin loci for the microseisms of different period. These short period microseisms correlate closely with the passage of the cold front eastward over close coastal waters.

The standard photographic galvanometer seismographs at Palisades showed a normal background during this entire interval. The electronic seismograph showed microseism activity with trends similar to those of the resonant seismometers, but with a lag in short period response.

*January 17–18, 1953*

Very striking microseism activity is shown on the 5.7-sec trace in Figure 5 with a matching, but much weaker effect on the 6.8-sec band. The 2.0-and 3.0-sec channels are at background, indicating that maximum signal strength is probably close to, but somewhat above, 5.7 sec. Direct measurement on standard records gives 5.9 to 6.1 sec for the dominant microseism period at this time.

The weather chart in Figure 6 shows a very intense low pressure area between Labrador and the southern tip of Greenland. This cyclone is considered to be the generating area for the microseism storm of Figure 5. The long period microseisms commenced about the time the cold or western portion of the cyclone traveled out over the deep water area beyond the 1,000-fm line (dotted). Maximum 6-sec microseism intensity was noted in the preceding case with a steep pressure gradient over the same region, and similar relationships have been observed for many other such situations.

*November 5–6, 1952*

A marked increase in signal strength occurs toward the end of November 5 on the 7.0 sec channel in Figure 7. These microseisms declined to a fairly constant although high intensity level by 0500 of November 6. The 3.0-and 4.5-sec traces show a continuously high level during the interval and with a definite but slight increase (more marked on the latter) as the 7-sec microseisms decreased. Microseism period measured on standard records during the interval of maximum intensity was 6.0 to 6.5 seconds, with a decrease to 5–5.5 sec following the maximum. The latter probably explains the increase in signal on the middle channels as intensity decreased on the upper (7-sec) channel. The 1-and 2-sec bands are conspicuously quiet during this interval.

The related weather is shown on the four charts of Figure 8, which illustrate rather typical progress and intensification for this region of the low pressure area indicated. According to the chart at 1230, November 5, the cyclone, although of moderate intensity, extended from deep water northward to the coast. The storm

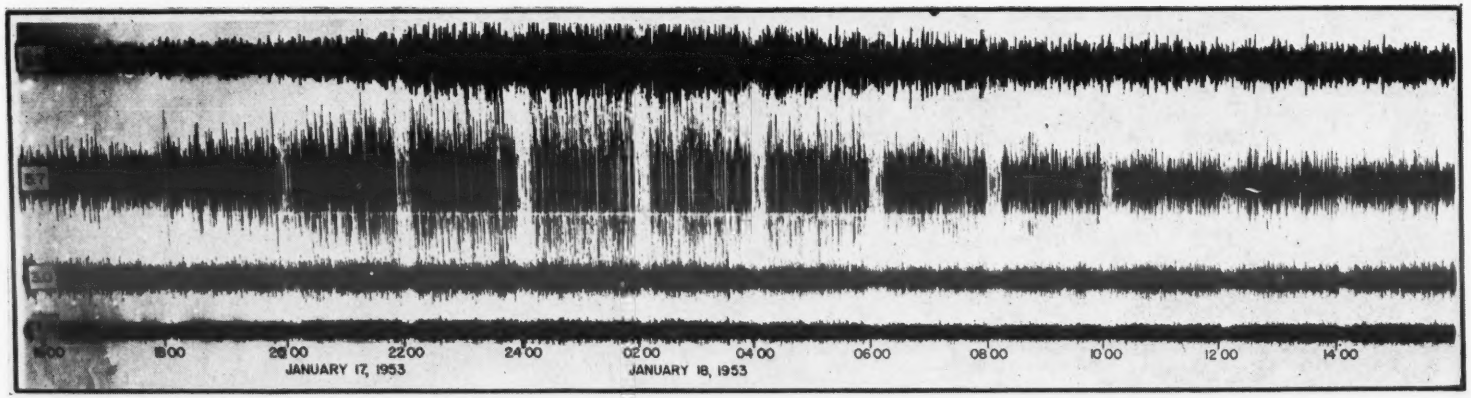


FIG. 5. Resonant seismograph record of January 17–18, 1953 showing microseisms associated with low pressure area shown in Figure 6.

strengthened considerably in the next six hours as it became smaller and more circular with approach to the coast. Simultaneously, the long-period microseism signal (Figure 7) began to increase, and reached maximum strength when the storm center and area of maximum wind velocity was just at the edge of the continental shelf. The storm intensified further as it moved almost completely over the shelf by November 6 at 0630. During this latter interval long period microseisms decreased while the shorter period signal increased somewhat. The steep pressure gradient which persisted eastward from Newfoundland as the central area of the cyclone moved northward over land appears to explain the

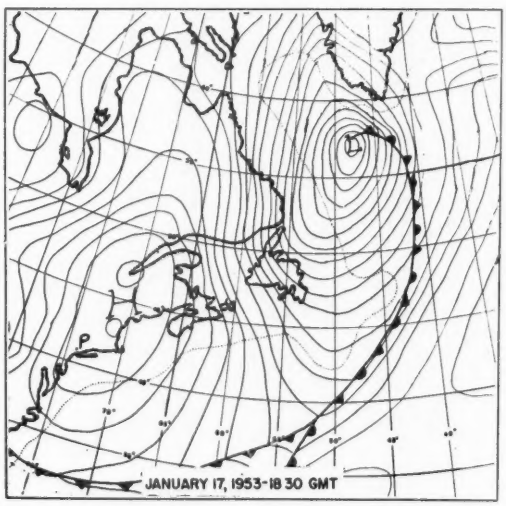


FIG. 6. Weather chart of Northwest Atlantic Ocean area for January 17, 1953.

continuing broad microseism spectrum after the interval of maximum intensity.

Since the short period microseism signal (3.0–4.5 sec) was relatively uniform, it is concluded that it was generated over the shelf zone both preceding and following the passage of the central area of the cyclone. The slight increase in intensity corresponding to the time of passage of the intense central area of the cyclone over the shelf also supports this view. The generation of the intense long period microseisms seems to be related to the position of the cyclone when adjacent to or at the edge of the shelf.

It seems noteworthy that the cyclone traveled almost due north along the 55th meridian. From this fact, and the pattern of wind-flow deduced from the isobars, it seems unlikely that transposition of the two main fetches (north in the west portion and south in the east portion) could have occurred. Thus the possibility of microseism generation through ocean-wave interference in this case seems doubtful.

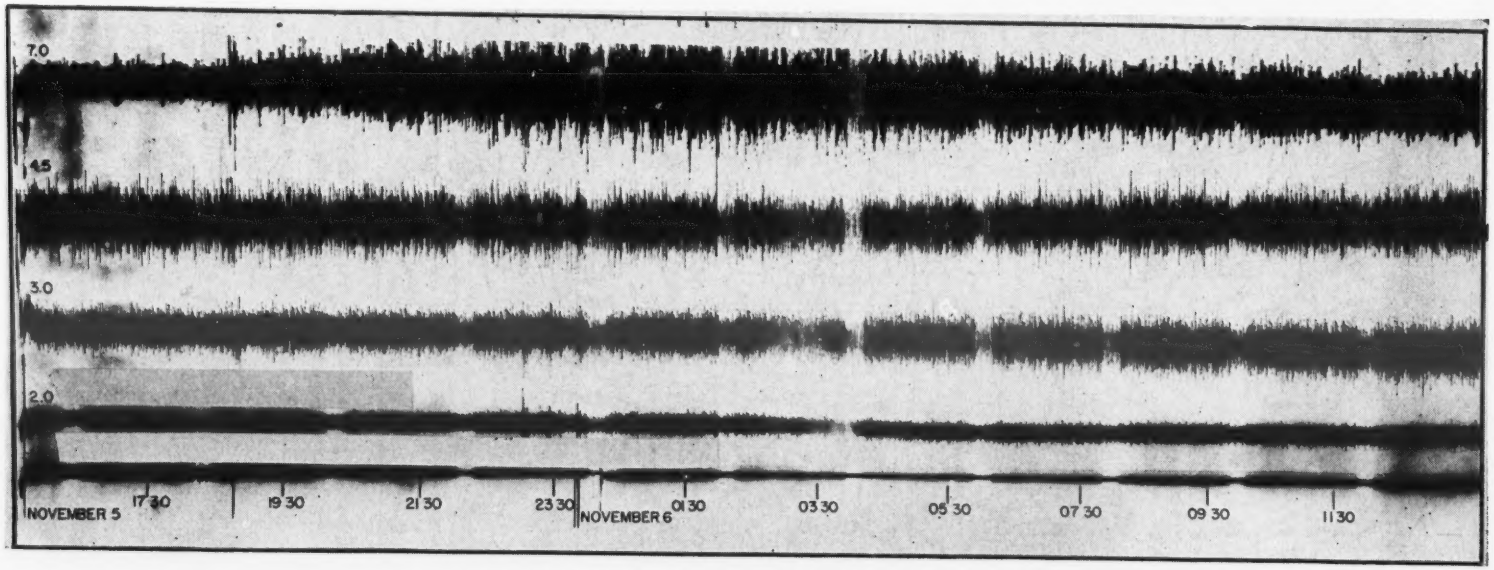


FIG. 7. Resonant seismograph record for November 5–6, 1952.

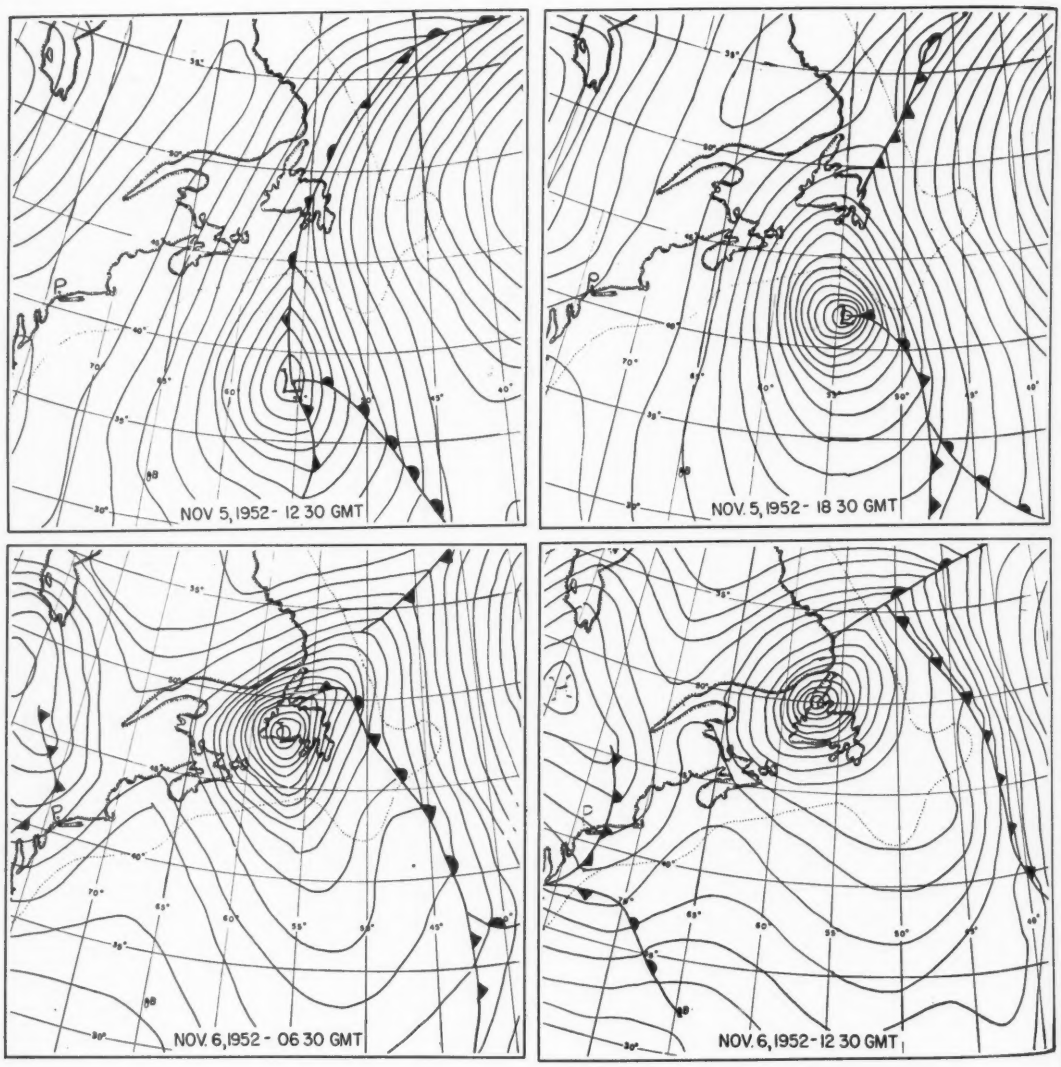


FIG. 8. Weather charts showing progress of low-pressure area on November 5–6, 1952 associated with microseisms of Figure 7.

*November 18–19, 1952*

The three weather charts in Figure 9 show the intensification of a cyclonic area in much the same position as in the previous case. Note, however, that the storm is practically stationary over the 36-hour interval. This appears to preclude the possibility of wave interference resulting from the transposition of wave fetch. Between 1830 November 18 and 0630 November 19, the area of maximum wind increased as the intensity in the central zone diminished somewhat.

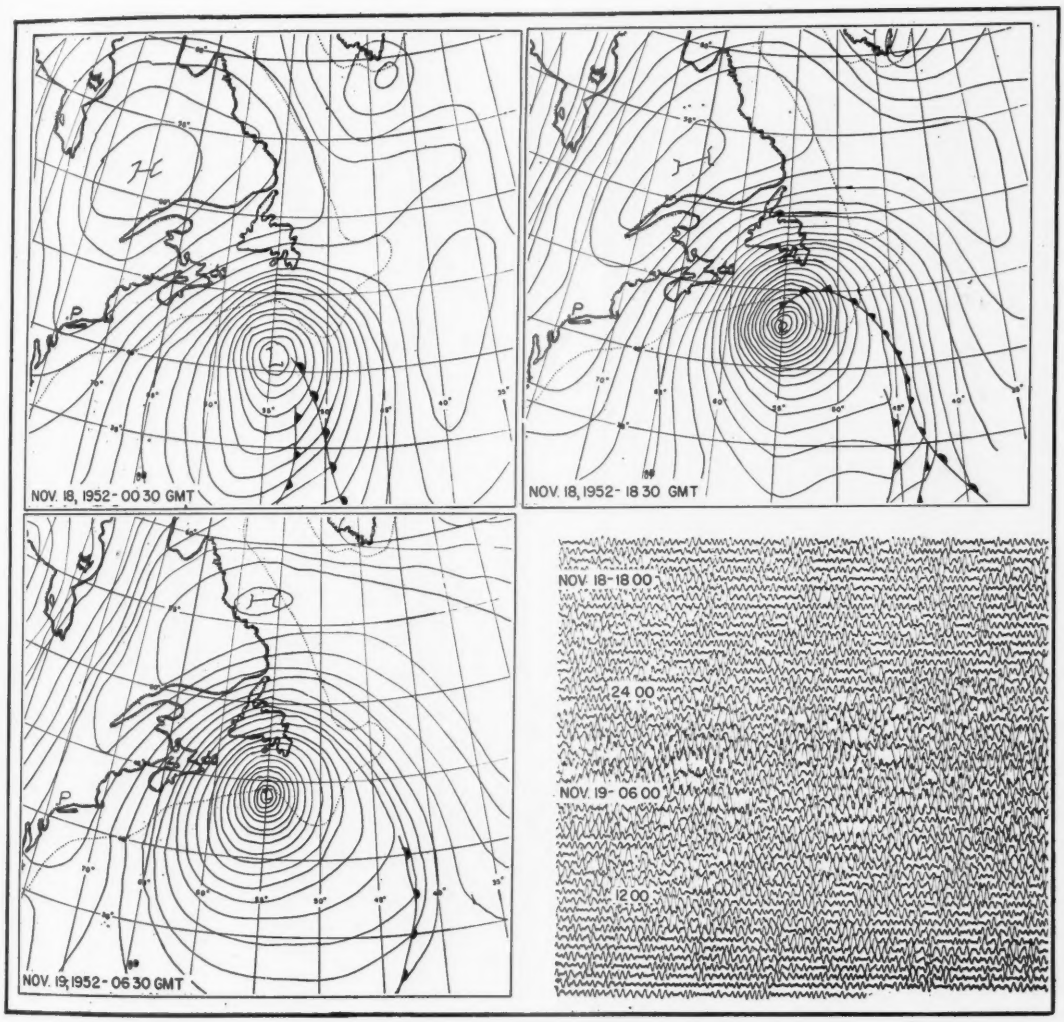


FIG. 9. Weather charts and standard seismogram for storm of November 18–19, 1952.

Microseism period measured on the Palisades (Columbia) vertical seismogram: $T_0 = 12$, $T_0 = 15$ (lower right) increased to 8.5 sec by 0600, November 19, the time of maximum cyclone area.

Resonant seismograms ($T_0 = 1.0$, 2.0, 3.0, 4.5 and 7.0) for November 17–19 are reproduced in the two sets of records in Figure 10. Maximum signal strength shows on the 7.0-sec band from 1400 November 18 to 0200 November 19, coinciding with the time of 7-sec microseisms on the standard seismogram. As period increased to 8.5 sec, signal strength on the 7.0-sec band decreased.

As in the preceding case, maximum microseism activity appears to be related

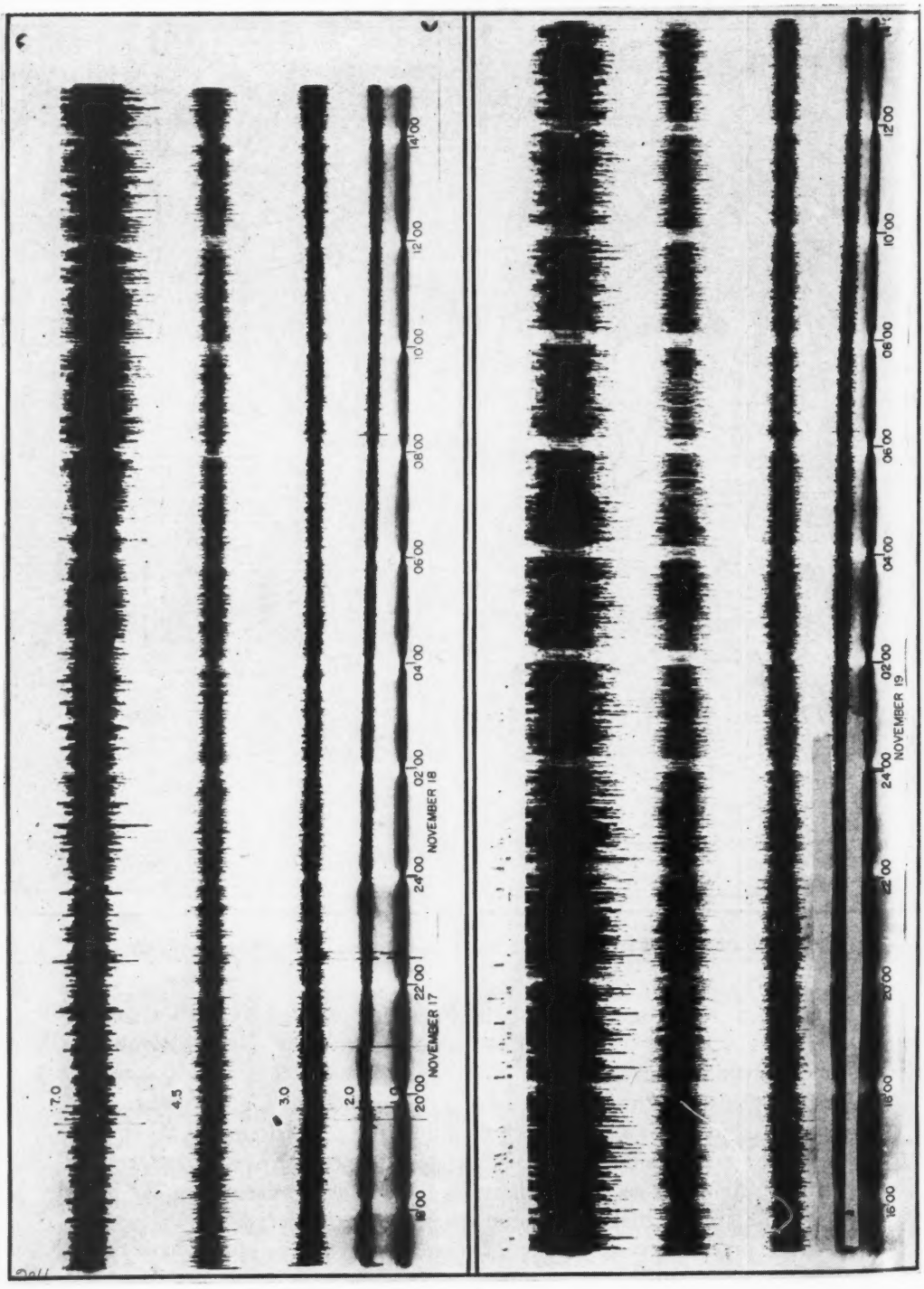


FIG. 10. Resonant seismograms for period from November 17–19, 1952. These should be compared with standard seismogram of Figure 9.

to the proximity of the generating area to the edge of the continent as indicated by the 1,000-fm contour. It may also be significant that microseisms of longer period, 6.5 to 8.5 sec, are associated with the two storms south of Newfoundland, whereas shorter periods are associated with the two storms between Labrador and Greenland. The straight isobar pattern occurring with the latter storms would be expected to provide much greater fetch for the development of long period ocean waves than would the more circular pattern of the cyclone south of Newfoundland. It may be relevant to note that a rather limited deep zone exists about 42° N. between 50° and 65° W. Bathymetric charts indicate a depth of more than 2,900 fm and recent seismic refraction indicates that there is about 2 km of sediments below the water bottom. This may well be related to the relatively long period of the microseisms generated in this region.

*March 29–30, 1953*

In the seismogram at the top of Figure 11, note that the lowermost trace is for the longest period, in this case 8.0 sec. Following upwards in order, $T_0 = 2.0$, 3.0, 4.5 and 6.7 sec. The 8-sec channel shows a very strong signal commencing about 1600, March 29 and continuing for the duration of the record, with maximum strength between 2200, March 29 and 0800, March 30. The quiet 6.7-sec band indicates the lower limit of the spectrum and suggests that the peak period is longer than 8 sec. The increasing signal on the 2-, 3-, and 4.5-sec channels is therefore related to a different microseism source.

Reproductions of the vertical component records from the Palisades (Columbia) and Benioff seismographs are shown in "B" and "C" respectively. The measured period of the dominant microseisms (which are poorly recorded by the Benioff) is 8.5 to 9 sec. This long period signal, which is not detectable until 1900 on B and 2200 on C, is clearly preceded by the signal beginning at 1600 on the 8.0-sec resonant channel. Also, although the 8-sec intensity continues at more than one-half maximum following 0800 on March 30, the long period microseisms become masked by increase in short period microseisms after 0800 on the standard records (B and C).

The long period 8.5- to 9.5-sec microseisms are correlated with an intense low pressure system off the southern coast of Alaska. Ground particle trajectories for the horizontal plane constructed for these microseisms give elongated orbits whose long axes coincide in direction with the azimuth of the storm. This has been determined to be a rather frequent occurrence, although the microseisms are often masked by more intense shorter period microseisms from Atlantic storms. The short period microseism storm becoming prominent during March 30 has been correlated with a close Atlantic cyclone. The records from the resonant seismometers clearly distinguish between the two microseism storms and permit the study of the amplitudes as a function of time without interference of the separate signals.

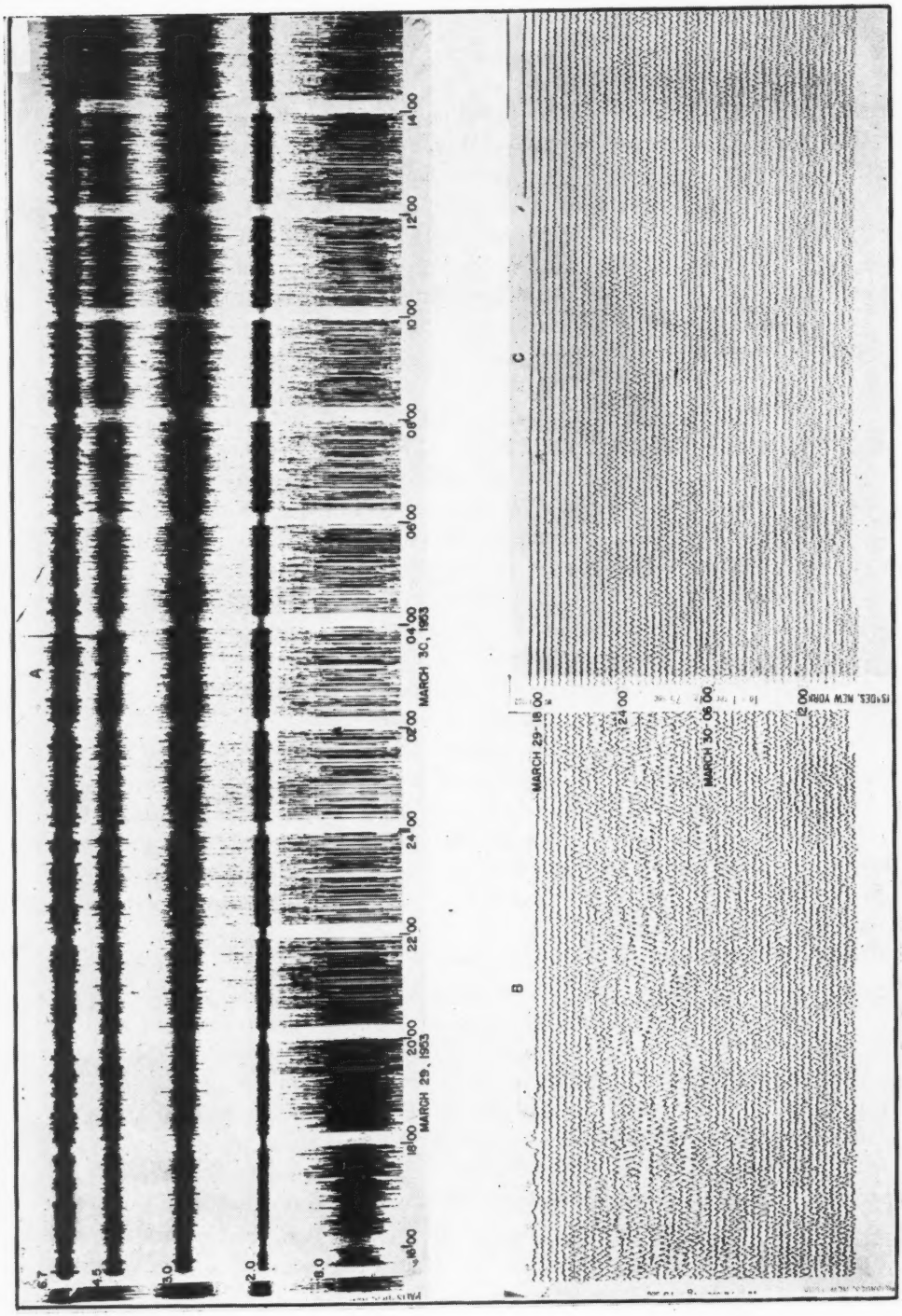


FIG. 11. A) Resonant seismogram for March 29–30, 1953 compared with B) Palisades seismograph record and C) Benioff seismograph record for same dates.

*August 14–15, 1953 (Hurricane "Barbara")*

The track of Hurricane "Barbara," 1953 is shown in Figure 12 together with a plot of Palisades microseisms showing amplitudes as a function of storm position as well as of time. Note that the hurricane center was well on the continental shelf for most of its path.

Figure 13 reproduces records from the three resonant seismometers in operation at the time. These had $T_0$ values of 3.0, 4.0, and 6.0 sec. Maximum signal strength is shown by the 3- and 4-sec channels, which show essentially simul-

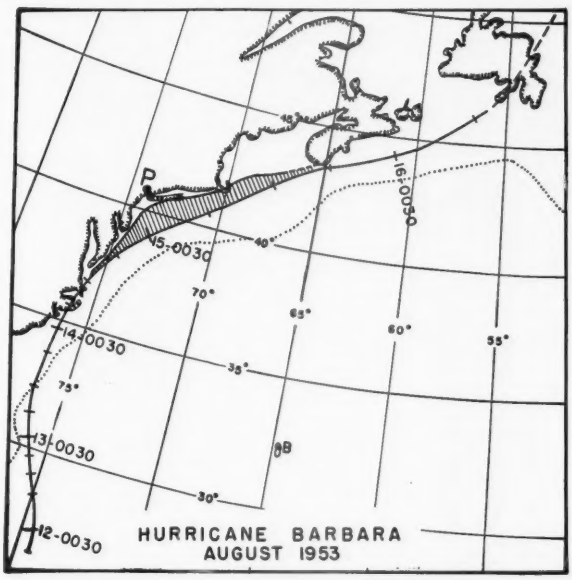


FIG. 12. Track of Hurricane "Barbara," along Atlantic coast, August 14–15, 1953.

taneous beginnings and maxima. Period on standard seismograms was measured at 3.5 to 4 sec. The 6-sec band differs from the others in that the signal appears much weaker and begins about two hours later.

In previous cases (discussed in this report and elsewhere) microseism period increased or decreased when generating areas moved transverse to the continental shelf. As water depth increased uniformly over the shelf a direct relationship between depth and period was suggested. In the present case water depth beneath the hurricane track is essentially constant during the interval of Palisades microseism activity. These observations are in harmony with a depth-period effect.

The microseism-generating area of the hurricane was broader than the narrow center path and actually extended from the coast out to deep water just beyond the shelf. The weak signal on the 6-sec channel is explained as the response to the 4- to 5-sec microseisms that are usually recorded from wind systems over the deeper water zone. The response is weak in part from being out of resonance with

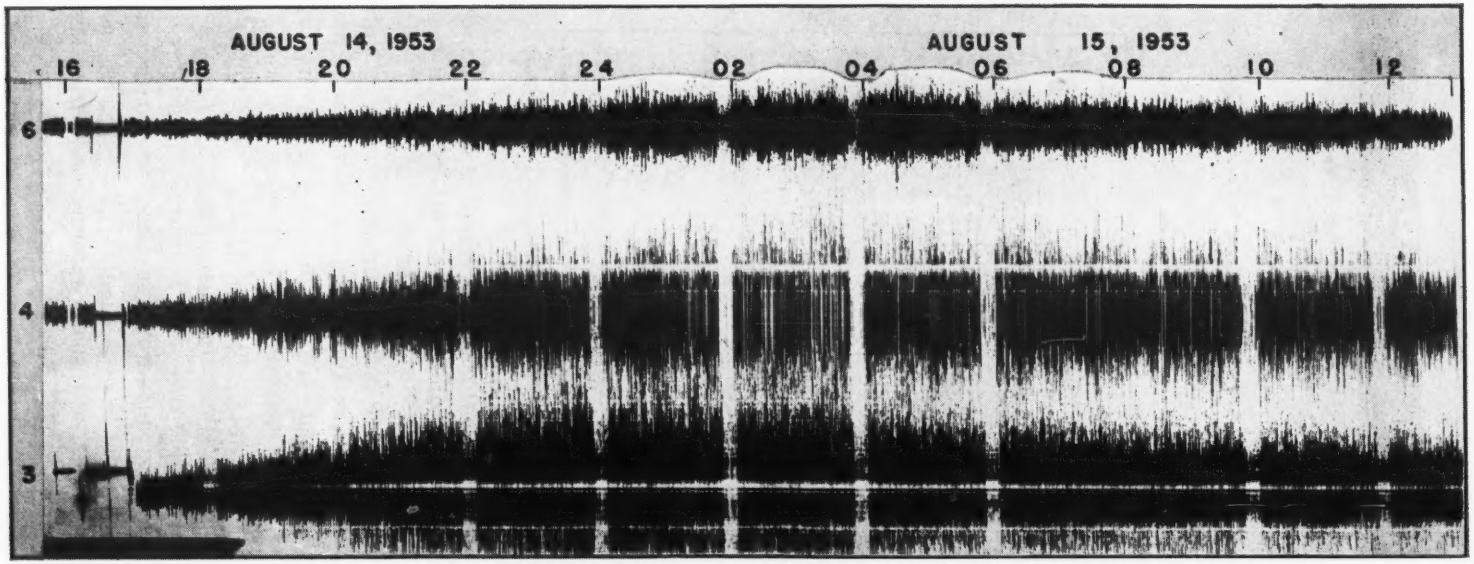


FIG. 13. Three resonant seismograms showing microseisms associated with Hurricane "Barbara" August 14–15, 1953.

the signal, and in part on account of the small portion of the hurricane that existed over the deeper water. If the microseisms were generated by ocean waves arriving locally, it would be expected that the longer period response should have occurred earliest, which is not observed here.

## CONCLUSIONS

The study of many case histories of microseism storms having varied generating sources and locations indicates that the resonant seismometers:

(1) Have an improved signal-to-noise ratio which permits either earlier detection of microseism storms or detection of microseisms which may not otherwise be known to exist.

(2) Permit distinction between simultaneous microseisms from different sources.

(3) Show progressive increase in period of frontal microseisms as fronts move seaward from the eastern coast of North America.

(4) Show definite differences in period characteristics among different regions of microseism generation.

(5) Permit quick determinations of microseism intensity as a function of time, and show clearly the spectral distribution of microseism energy.

(6) May, as a result of the above qualities, be a valuable tool in any continued study of hurricane location by means of microseism amplitude comparisons; this is of particular value when simultaneous storms are present, a very frequent occurrence in the Gulf of Mexico and in the Caribbean area.

## ACKNOWLEDGMENTS

We gratefully acknowledge the contributions of Bernard Luskin in the initial design and construction of the seismometers and of Harold Smith in their installation and maintenance.

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GEOPHYSICS, VOL. XIX, NO. 4 (OCTOBER, 1954), PP. 820–824

# NON-TECHNICAL PAPER

## GEOPHYSICAL MANAGEMENT LOOKS AT SAFETY AS A PUBLIC RELATIONS FACTOR*

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ABSTRACT

The public relations value of a good safety program is stressed. Public relations is not something that can be turned on and off at will; every company in every industry has it, whether it is wanted or not.

It has only recently become clearly appreciated that every safety activity has public relations value—good or bad. Just doing a good job on safety isn't enough; the job is not completed until the public and clients are made aware of the fact.

A worthy objective of safety then should be to create the most favorable human relations possible. The prevention of accidents by increasing safety activity within the industry is but one of the factors leading to betterment of public and employee relations within the geophysical exploration industry.

The evaluation of safety with respect to its effect on public relations is no light undertaking. Public relations was not invented the day before yesterday—it has always existed, whether we have wanted it or not. It is more than a function or a state of mind. It is really a relationship or atmosphere—good, bad, or indifferent—that exists between a company and the public. It is the business of making friends; it is the establishment of good conduct *plus* getting credit for it.

Having introduced public relations, let's look at safety. One broad definition of safety is "the prevention by foresight of disastrous results of chance happenings." Even technically trained men tend frequently to make light of safety work —to regard themselves as leading charmed lives, perhaps because of their greater familiarity with engineering and scientific processes. Safety work should not be beneath the dignity of either scientists or engineers; in fact, their technical training can make them most valuable in solving many safety problems. A good example would be the offsetting of electrostatic hazards in the storage and handling of electric detonators and highly volatile liquids. As we all know, G. M. Kintz and associates in the Bureau of Mines, as well as the engineering staffs of the electric cap manufacturers, have contributed greatly in this area.

Safety lies in both *knowing* and *doing*—realizing all the while that there will be consequent and corresponding effects upon public attitude. The objective is to influence this public attitude positively by acquiring a safety record to be proud of, then telling the world about it.

Safety may be thought of as one leg of the tripod of human relationships. The other legs are industrial relations and public relations. Remove one leg and such

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a tripod collapses. The natural effect of safety upon public relations has not until recently been clearly appreciated. Safety and public relations have another factor in common: Each one has been almost woefully neglected, particularly in the petroleum exploration industry, until a few years ago.

Perhaps the most important ingredient of any accident prevention program is consistent *seriousness*—continuous and relentless, regardless of time, method, or changing conditions. Safety thinking and planning for control must start at the top. This means that any attitude of indifference or of divided policy on the part of management will become apparent to employees, with resultant over-all failure of the safety program.

Another essential element in a successful safety program is well-considered publicity and education within the organization—untiring and repeated emphasis of the fact that safe thinking is a vital part of each worker's state of mind. It should be clear that safety begins from the moment the design of new equipment is started, from the inception of a new operation, from the moment a new employee is hired. The safety program is a unique link in management's liaison with all employees, especially as they are made aware of reciprocal benefits. Effective supervision, employee relations, client acceptance, public relations, service continuity, productivity, decreased absenteeism, reduction of waste—all are enhanced by a well-planned and properly administered accident prevention program to the mutual benefit of employee and employer alike. Also important—as indicated by G. H. Westby at the Houston meeting—the petroleum industry stands to gain immeasurably through exploration service of increasing effectiveness. In the final analysis, the public has a real stake in the issue, for unsafe methods are recognized as being inefficient, with consequent effect upon the cost of finding new petroleum.

Safety procedures and regulations are important, but an individual, thinking properly, cognizant of and willing to accept his responsibility, can do more than all the rules and procedures ever written. Nor is a sound accident prevention program built entirely on safeguards; that is, gadgets, hard hats, safety shoes, goggles, posters, contests, and awards. These are, of course, important and necessary adjuncts but by no means substitutes for the proper condition of mind that is necessary to make a safety program really successful.

A very large part of our safety effort must, therefore, be directed into channels where the individual worker learns to believe that safety is not solely the job of the safety director, or the safety committee, or of management—but an important element of his own job, his personal responsibility, his way of life; and having become safety-conscious himself, then naturally to go all out selling it to his fellow workers. We must charge the atmosphere of our working environment with the spirit of safety, so that accidents will be well nigh impossible.

When you get right down to it, safety is just *efficiency*. If the procedure is right, if the equipment is properly designed, if it is used correctly for the purpose intended, and if the worker is trained properly in his job, safety takes care of

itself ninety-nine percent of the time. The one-hundredth occasion is the unforeseen and unforeseeable event.

Accidents can be prevented. The evidence is all about us in numerous living examples. But we've got to stop being complacent by making safety a personal matter—by restricting it to an individual sphere of influence. We must discard that outworn defeatist attitude that "accidents just happen"—that they are a part of living—that it's just human nature to get hurt, and all that sort of foolishness! Sure, we used to think that smallpox, diphtheria, typhoid, and many other dread diseases were a part of our lot in life. We seldom see them today. Why? Because people collectively did something about them. Thus, there must be a way to divorce man from accidents as well. This may sound idealistic—too hopeful—but it's a most worthy objective. We must agree, though, that to approach this ideal demands continuing hard team work.

The mind of the public can harbor certain spontaneous and sometimes strange associations. Thus, all geophysical companies have at times experienced unfavorable reactions from townspeople and landowners because of experience that preceded them; wrong, perhaps, but still persistent "idea associations" in people's minds.

Our objective should be to displace those false ideas with correct ones. When the word "geophysical" is mentioned, we want the association in the public mind to be clearly, without hesitation, and justifiably, "the most safety-minded industry in the world." Now, how is this attained?

At first glance the very nature of the geophysical exploration industry would seem to make safety improvement a hopeless task. Such factors as widespread and highly mobile type of operations; youthful, immature, and untrained personnel; and high rate of helper turnover are some of our special brands of difficulties. These factors are yielding, however, as our relatively new industry continues to gain maturity, but they will always be with us to some degree. In aggressively coping with the vagaries of Mother Nature, as well as human nature, the geophysical exploration industry has long since demonstrated that it would be fully equal to accepting such a challenge. It does call for endless patience, ingenuity, and tact, coupled with expert knowledge of the varied operations. Significant improvement in accident rates has been made by a number of individual companies in the geophysical exploration industry. The industry as a whole has benefited thereby, but the geophysical accident frequency rate of 1952 is still comparable with that of the coal mining industry and nearly three times that of the petroleum industry as a whole. Even so, we have some encouragement to report, for a 45 percent improvement for the exploration industry is noted in 1952 over 1951. It is estimated that the industry benefited therefrom by approximately a half-million dollars.

Just doing a good job on safety isn't enough. If the public and the contractors' clients are not aware of what we are doing, our job isn't completed. We need to make friends with our good safety record. Safety attainment is a "natural" for

this purpose—comprising the best expression by a company of its sincere interest in good human relations.

Practically everything which is done in any *safety* program has *public* relations value—good or bad. Let a company achieve a good safety record, and little notice is taken of the fact in the everyday press—unless we see that it is publicized or dramatized. But, let a company have an explosives disaster, a bad fire, a serious highway accident, and it becomes the subject of widespread headlines. One of the greatest contributions that a safety program can make to good public relations is the bad headline it can prevent.

Thanks to the work of the Society of Exploration Geophysicists' Committee on Safety, the geophysical exploration industry today enjoys a 45 percent lower frequency rate than was the case a mere two years ago. This is a remarkable accomplishment and consequently of great credit to the SEG councils and the special committee so ably launched by Bart W. Sorge a few years back.

I might recount the many stock arguments relating to the desirable effects on public relations which result from an active and successful accident prevention program, and, conversely, the unsatisfactory results from an indifferent one, or the lack of one, but I will assume these facts are already well known. Employees with low morale because of working in a group that has frequent accidents talk things over with their friends—the public—because it seems to be human nature to spread bad news. Such adverse gossip can spread fast. On the other hand, if there is evidence that a company, large or small, is conscientiously sponsoring and applying a safety program, then the particular employees have concrete, unquestionable evidence of the company's interest in the prevention of accidents. They then find it natural to challenge anyone who expresses any idea that the company cares nothing about their welfare.

We are impressed that the public mind is often peculiarly receptive to the idea that a company has no heart. Therefore, there should not be the slightest doubt in the minds of management that an effective safety program and the resulting good record comprise valuable human relations—whether it be from the viewpoint of employee relations, client relations, or public relations, and perhaps government relations.

Whenever government relations are mentioned, one is immediately reminded of the increasing effort to legislate accident prevention programs in many fields of industry. I think we hardly need mention the difficulties that might follow should such outside control be exercised over the exploration industry. However, it is axiomatic, I believe, that unless we clean our house, someone else may do it for us.

Wherever it has been tried, state or federal safety regulations have not proved particularly successful—for such regulations often tend to inadequacy in meeting even minimum standards. Frequently the job requirements are poorly understood, and the consequent regulations poorly drawn and even more poorly administered and enforced. Extreme specialization, such as would be required

for the geophysical exploration industry, would be impossible. In the end the average safety-minded management would not be satisfied with the results from such outside supervision.

The large gains obtained since the inception of the SEG campaign would clearly indicate that the task is still in its early stages. We can still obtain rich rewards in terms of reduced insurance costs and better public relations as all contractors, particularly the smaller ones, take an active part in an integrated safety program. There are other benefits which such a safety program could offer the industry. The preparation and promotion of "recommended safe practices" comes to mind, as does also protection of the industry against excessive and unreasonable responsibilities. Either of these alone, through enhanced public relations, would benefit the exploration industry as a whole. Of great benefit also would be a more complete working relationship with such associations as the National Safety Council, the American Petroleum Institute, and others in an ever expanding safety program.

An effective safety program cannot be had without paying for it; therefore, dollars and safety should be mentioned together as a practical step toward inducing an effective plan. Certainly the absence of a good safety program could tend towards red ink in the profit-and-loss statement. The profit on such a program may be intangible; at the same time, it may affect many items in the financial statement.

Most important of all, safety is an inseparable part of the problem of operation—one that can and must be administered by operation management. It has been said that "there is more to management than just the process of growing old in a particular business." Likewise, there is more to safety than just providing the means for a man to grow old in his job rather than to become disabled or killed by it.

It is undoubtedly becoming more difficult for a business enterprise to compete successfully and to grow in the open market without both a safety program and a public relations program. The results of a safety program may not be measured directly or entirely in terms of money, for one must also consider the beneficial effects upon human relations—employee and public alike.

Summing up, then, it is seen that well-administered safety planning contributes to sound industrial relations between management and the worker, while this relationship in turn is reinforced by effective public relations.

The acme of good public relations is achieved whenever management establishes and vigilantly maintains a safe industry in which to work.

I wish to acknowledge the benefit of inspiration and many valued suggestions in preparing this paper from John Imle, currently chairman of the SEG Safety Committee.

# DEPARTMENTS

## PATENTS

O. F. RITZMANN*

### ELECTRICAL PROSPECTING

*U. S. No. 2,675,521.* P. R. Geoffroy and T. Koulomzine. Iss. 4/13/54. App. 10/1/52.

*Method of Geophysical Exploration through the Use of Boreholes.* A d-c electrical prospecting system in which two current electrodes are placed on the surface of the ground on a line between two drill holes or on a line at right angles thereto, and two potential electrodes are kept at equal depths in two drill holes and moved vertically in the holes.

*U. S. No. 2,677,801.* L. Cagniard. Iss. 5/4/54. App. 10/6/50 and 9/24/51. Assign. Centre National de la Recherche Scientifique.

*Geophysical Exploration Method.* An electromagnetic prospecting method in which variations in the electric telluric field and the magnetic field of the earth for the same area are simultaneously recorded.

*U. S. No. 2,680,226.* S. Whitehead and B. Roston. Iss. 6/1/54. App. 1/24/45, 1/9/46 and 6/16/51. Assign. E.R.A. Patents Ltd.

*Location of Conducting and/or Magnetic Bodies.* A pick-up circuit for an electromagnetic-prospecting system using two co-axial, co-planar coils of different turns-area, one coil being mounted inside the other, and in which the difference between their generated emfs is measured.

### GRAVIMETRIC PROSPECTING

*U. S. No. 2,674,885.* D. Silverman. Iss. 4/13/54. App. 8/17/49. Assign. Stanolind Oil and Gas Co.

*Gravity Meter Motion Compensator.* A motion compensator for a gravimeter which has a motion detector fastened to the gravimeter base with the output of the motion detector adjusted in phase and added to the gravimeter signal.

*U. S. No. 2,674,886.* J. F. Evans. Iss. 4/13/54. App. 8/17/49. Assign. Stanolind Oil and Gas Co.

*Self-Leveling Instrument Mounting.* A self-leveling gravimeter support having a hemispherical outer bowl containing liquid whose buoyancy supports a major part of a gimbal-suspended hemispherical inner bowl on which the gravimeter is fastened.

*U. S. No. 2,674,887.* S. P. Worden. Iss. 4/13/54. App. 12/8/47. Assign. Texas Instruments Inc.

*Gravity Meter.* A gravity meter whose suspended system is made of quartz and having a supporting spring whose upper end is moved so as to change its force angle by adjustable nulling springs and a non-linear auxiliary spring which effects temperature compensation.

### RADIOACTIVITY PROSPECTING

*U. S. No. 2,675,480.* G. Herzog. Iss. 4/13/54. App. 3/9/48 and 3/19/51. Assign. The Texas Co.

*Prospecting.* A radioactivity prospecting method in which the time is measured for the same number of detector counts to accrue at each location.

* Gulf Oil Corporation, Patent Department Pittsburgh, Pa.

*U. S. No. 2,677,780.* H. V. Rees and A. L. Tirico. Iss. 5/4/54. App. 12/28/51. Assign. Texaco Development Corp.

*Radiation Detector.* A multiple-plate radioactivity detector in which the anode wires pass through holes in the cathode plates and which has auxiliary anode wires outside the array of plates.

*U. S. No. 2,678,398.* G. Herzog. Iss. 5/11/54. App. 3/9/48 and 3/19/51. Assign. The Texas Co.

*Prospecting.* An airborne radioactivity prospecting method in which a number of different radioactive sources are placed on the ground at known locations, the airborne detector output being integrated with time, and the aircraft elevation adjusted so that each source gives a distinctive pattern against the background.

SEISMIC PROSPECTING

*U. S. No. 2,675,086.* D. H. Clewell. Iss. 4/13/54. App. 5/3/48. Assign. Socony-Vacuum Oil Co., Inc.

*Method and Apparatus for Seismic Prospecting.* A seismic prospecting system in which a continuous-wave ground vibrator at the shot point is abruptly stopped and the decay of the vibration at the geophone stations recorded.

*U. S. No. 2,675,525.* T. H. Wiancko. Iss. 4/13/54. App. 6/25/51.

*Accelerometer.* A variable-air-gap magnetic-bridge-type seismometer having a bar-shaped armature with an auxiliary mass on one end so as to make it dynamically unbalanced.

*U. S. No. 2,675,533.* R. R. Brown. Iss. 4/13/54. App. 3/26/51. Assign. Phillips Petroleum Co.

*Seismometer.* A moving-coil electrodynamic seismometer in which the coil-suspending springs are fastened to flanges on the upper end of the coil form and removably mounted on the annular top plate of the magnet system.

*U. S. No. 2,675,882.* C. B. Bazzoni and L. G. Ellis. Iss. 4/20/54. App. 11/12/49. Assign. Sun Oil Co.

*Seismographic Prospecting.* A method of seismic shooting in which a spiral of explosive cord, with or without concentrated charges distributed along its length, is detonated on the ground to give a desired form of seismic wave front.

*U. S. No. 2,676,206.* W. R. Bennett and L. C. Peterson. Iss. 4/20/54. App. 12/6/51. Assign. Bell Telephone Laboratories, Inc.

*Computation and Display of Correlation.* Apparatus for making a correlation analysis of a signal recorded on a magnetic tape by reproducing the signal and feeding it to one side of a multiplier circuit, feeding to the other side of the multiplier circuit a standard or comparison signal with varying time delay, integrating the multiplied output over a predetermined time interval, and recording the product.

*U. S. No. 2,677,270.* G. E. Sanderson. Iss. 5/4/54. App. 3/25/49. Assign. Lockheed Aircraft Corp.

*Vibration, Acceleration, Pressure, and Position Pickup Device.* A vibrometer having a case of electrically-insulating material with three internal annular electrode rings, the case being filled with a conducting liquid in which an insulating moving unit is immersed adjacent the electrodes.

*U. S. No. 2,677,729.* W. H. Mayne. Iss. 5/4/54. App. 7/9/52. Assign. Olive S. Petty.

*Differential Amplifier.* A differential amplifier in which the two input voltages control tubes whose plate circuits are connected in a bridge circuit from which the differential output is obtained.

*U. S. No. 2,678,107.* J. P. Woods. Iss. 5/11/54. App. 11/9/49. Assign. The Atlantic Refining Co.

*Apparatus for Eliminating Horizontally Traveling Waves.* A seismograph mixing system in which a frequency band of horizontal waves is eliminated by using two geophone arrays of unequal lengths

combined in parallel, with each array arranged to have zero response for horizontal waves of a predetermined frequency.

*U. S. No. 2,679,205.* R. G. Piety. Iss. 5/25/54. App. 2/18/49. Assign. Phillips Petroleum Co.

*Method of and Apparatus for Producing Seismic Waves.* A device for electrolytically generating an explosive gas mixture in a seismograph shot hole and igniting it by an electric spark.

*U. S. No. 2,679,636.* C. Hillyer. Iss. 5/25/54. App. 3/25/52.

*Method of and Apparatus for Comparing Information.* A system for correlating two series of waves in which the difference between concurrent instantaneous amplitudes is taken to obtain a third series of waves whose instantaneous amplitudes are integrated to determine the degree of match.

WELL LOGGING

*U. S. No. 2,674,049.* I. J. James, Jr. Iss. 4/6/54. App. 11/16/48. Assign. Union Oil Co. of Calif.

*Apparatus for Subsurface Exploration.* A well surveying apparatus having a gravity-sensitive device carrying movable plates of two condensers whose capacity change alters the frequency of two oscillators.

*U. S. No. 2,674,699.* F. S. Phillips. Iss. 4/6/54. App. 2/11/50. Assign. Schlumberger Well Surveying Corp.

*Radioactivity Detecting Apparatus.* A radioactivity logging sonde having both a long counter and a short counter arranged to have different starting potentials so that the effective length may be varied by changing the applied potential.

*U. S. No. 2,675,481.* S. Krasnow. Iss. 4/13/54. App. 10/24/39 and 3/21/51. Assign. Schlumberger Well Surveying Corp.

*Borehole Radioactivity System Utilizing Radio Signal Transmission.* A radioactivity logging system in which the radioactivity detector modulates a radio transmitter in the sonde whose wave length is comparable with the borehole diameter so that the borehole acts as a wave guide and the radio signal is picked up at the surface.

*U. S. No. 2,676,489.* R. B. Basham. Iss. 4/27/54. App. 10/2/50. Assign. Westronics, Inc.

*Apparatus for Measuring Temperature in Boreholes.* A borehole thermometer using two negative coefficient resistors connected in an a-c circuit with rectifiers so that both the absolute temperature and its gradient can be recorded.

*U. S. No. 2,677,996.* C. Laval, Jr. Iss. 5/11/54. App. 11/19/51.

*Borehole Camera Apparatus.* A borehole camera in a case surrounded by an expansible transparent membrane which is expanded by a transparent liquid through which the camera photographs the borehole walls.

*U. S. No. 2,678,397.* G. Herzog. Iss. 5/11/54. App. 10/21/50. Assign. The Texas Co.

*Method of and Apparatus for Exploring Radioactive Strata.* A gamma-ray logging system using a proportional counter which is made sensitive to gamma rays above a threshold energy by coating its interior surface with a material which gives off ionizing particles when activated by gamma rays whose energy exceeds the threshold.

*U. S. No. 2,679,161.* J. E. Yancey. Iss. 5/25/54. App. 11/3/49.

*Depth Progress Recording Apparatus for Wells.* A drilling rate recorder which marks operations other than drilling on one side of a zero line and on the other side of the line indicates time required to drill a specified distance.

*U. S. No. 2,679,182.* R. R. Proctor and D. J. Wangelin. Iss. 5/25/54. App. 8/26/48. Assign. The Pure Oil Co.

*Apparatus for Measuring Changes in Fluid Flow Velocity.* A subsurface well flowmeter in which a dye is automatically injected into the fluid stream at a constant rate and the color intensity measured photoelectrically.

*U. S. No. 2,679,757.* C. H. Fay. Iss. 6/1/54. App. 4/9/48. Assign. Shell Development Co.

*Apparatus for Recording Subsurface Measurements.* A system for signaling from a well instrument to the surface in which the well instrument changes the angular spacing between a movable and a fixed contact and a synchronous motor-driven sweep arm closes the contacts whose time sequence is recorded at the surface on a synchronous motor-driven drum.

*U. S. No. 2,680,201.* S. A. Scherbatskoy. Iss. 6/1/54. App. 6/5/50.

*Neutron Well Logging.* A neutron logging system in which the formations are bombarded with fast neutrons and the detector is surrounded by an absorber of slow neutrons and with a hydrogenous material to control the energy range of detected neutrons.

*U. S. No. 2,680,913.* M. O. Johnston and J. A. Moosman. Iss. 6/15/54. App. 8/10/51. Assign. Johnston Testers, Inc.

*Caliper for Determining the Shape and Diameter of Well Bores.* A caliper logging apparatus having arms which are held retracted by a sleeve released by a go-devil and which are connected to separate styluses recording on a common drum.

*U. S. No. 2,681,442.* G. A. Schurman. Iss. 6/15/54. App. 12/19/51. Assign. California Research Corp.

*Seismic Wave Velocity Logging Apparatus.* A borehole geophone having a large mass or heavy housing suspended from the cable and the geophone elastically suspended from the mass so as to isolate it from cable-borne vibrations.

*U. S. No. 2,681,567.* M. B. Widess. Iss. 6/22/54. App. 12/29/49. Assign. Stanolind Oil and Gas Co.

*System for Obtaining and Transmitting Measurements in Wells During Drilling.* A system of logging while drilling in which the measurement modulates a record material which is ejected into the drilling fluid and caught at the surface where the record is analyzed.

MISCELLANEOUS

*U. S. No. 2,674,877.* D. Silverman and R. E. Hartline. Iss. 4/13/54. App. 7/1/50. Assign. Stanolind Oil and Gas Co.

*Well Productivity Measurement.* A method of measuring well productivity by placing in the bottom of the well a slug of electrically identifiable deformable plastic whose movement up the hole is observed during production.

*U. S. No. 2,676,485.* F. Morgan. Iss. 4/27/54. App. 6/15/49. Assign. Gulf Research & Development Co.

*Method of Sealing Cores While Determining Their Permeability.* A method for sealing the outside surface of a porous core while making permeability measurements in which the outside cylindrical surface of the core is blanketed with a fluid phase which is more non-wetting than the flowing phase and maintained at a pressure greater than that of the flowing phase but less than the displacement pressure.

*U. S. No. 2,679,159.* E. S. Messer. Iss. 5/25/54. App. 1/21/50. Assign. Continental Oil Co.

*Determination of Irreducible Water and Other Properties of Core Samples.* A method of determining the irreducible water saturation of a core sample by saturating the sample with a liquid and plotting

a curve of loss of weight through evaporation against time and noting the point of curve inflection where cohesive forces begin to reduce the evaporation rate.

*U. S. No. 2,680,833.* F. N. Rothacker. Iss. 6/8/54. App. 10/24/50. Assign. H. M. R. Electronics, Inc.

*Earth Core Magnetic Analyzer.* A core-orientation apparatus in which the core is rotated between poles of a pick-up stator, the position of the core being indicated by the changing frequency of an oscillator with a variable condenser on the shaft which rotates the core.

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SELECTED LIST OF U. S. PATENTS ISSUED DURING THE SECOND QUARTER OF 1954

| *Patent No.* | *Subject** | *Patent No.* | *Subject* | *Patent No.* | *Subject* |
|---|---|---|---|---|---|
| 2,674,049[a] | 520 | 2,675,700 | 428 | 2,677,126 | 316 |
| 2,674,128 | 200 | 2,675,701 | 428 | 2,677,127 | 316 |
| 2,674,313 | 392 | 2,675,702 | 148 | 2,677,183 | 444 |
| 2,674,409 | 68 | 2,675,705 | 288 | 2,677,193 | 180 |
| 2,674,411 | 444 | 2,675,882[a] | 360, 136 | 2,677,194 | 16 |
| 2,674,423 | 16 | 2,675,962 | 68 | 2,677,270[a] | 4, 492 |
| 2,674,513 | 324 | 2,675,973 | 224 | 2,677,272 | 428 |
| 2,674,659 | 224 | 2,676,022 | 224 | 2,677,276 | 200, 460 |
| 2,674,695 | 200, 308 | 2,676,023 | 224 | 2,677,279 | 288 |
| 2,674,696 | 168, 196 | 2,676,196 | 484 | 2,677,427 | 40 |
| 2,674,699[a] | 304 | 2,676,206[a] | 68, 352 | 2,677,461 | 224 |
| 2,674,877[a] | 292, 116 | 2,676,212 | 224 | 2,677,514 | 16 |
| 2,674,880 | 148 | 2,676,236 | 484 | 2,677,727 | 224 |
| 2,674,883 | 460 | 2,676,264 | 236 | 2,677,729[a] | 344 |
| 2,674,885[a] | 180 | 2,676,265 | 200 | 2,677,758 | 316 |
| 2,674,886[a] | 180 | 2,676,268 | 308 | 2,677,772 | 308 |
| 2,674,887[a] | 180 | 2,676,269 | 308 | 2,677,780[a] | 304, 308 |
| 2,674,945 | 136 | 2,676,270 | 308 | 2,677,801[a] | 124 |
| 2,675,086[a] | 360, 76 | 2,676,317 | 316 | 2,677,819 | 316 |
| 2,675,429 | 224 | Re.23,819 | 216, 16 | 2,677,820 | 312 |
| 2,675,469 | 68 | 2,676,392 | 484 | 2,677,821 | 312 |
| 2,675,471 | 68 | 2,676,408 | 16 | 2,677,964 | 200 |
| 2,675,478 | 200, 308 | 2,676,409 | 444 | 2,677,996[a] | 280 |
| 2,675,480[a] | 308 | 2,676,411 | 444 | 2,678,107[a] | 356 |
| 2,675,481[a] | 304, 516 | 2,676,485[a] | 88 | 2,678,163 | 68 |
| 2,675,482 | 140, 308 | 2,676,487 | 140 | 2,678,178 | 16 |
| 2,675,483 | 140, 308 | 2,676,488 | 148 | 2,678,397[a] | 304 |
| 2,675,484 | 308 | 2,676,489[a] | 452 | 2,678,398[a] | 308 |
| 2,675,521[a] | 116, 124 | 2,676,491 | 16 | 2,678,399 | 308 |
| 2,675,525[a] | 4 | 2,676,868 | 324 | 2,678,421 | 228 |
| 2,675,533[a] | 376 | 2,677,019 | 484 | 2,678,424 | 160 |
| Re.23,813 | 484 | 2,677,105 | 160 | 2,678,425 | 68 |
| 2,675,620 | 200 | 2,677,120 | 16 | 2,678,439 | 316 |
| 2,675,627 | 520 | 2,677,123 | 148, 68 | 2,678,440 | 316 |

* A key to the subject classification system will be found in GEOPHYSICS, v. XII, p. 256–264 (April, 1947).

[a] Abstracted on preceding pages of this issue.

| Patent No. | Subject |
|---|---|
| 2,678,441 | 312 |
| 2,678,500 | 484 |
| 2,678,559 | 12, 140 |
| 2,678,561 | 16 |
| 2,678,564 | 16, 216 |
| 2,678,581 | 420 |
| 2,678,772 | 68 |
| 2,678,804 | 392 |
| 2,678,967 | 484 |
| 2,678,970 | 224 |
| 2,678,971 | 224 |
| 2,678,972 | 224 |
| 2,679,010 | 196, 420 |
| 2,679,011 | 308 |
| 2,679,013 | 68 |
| 2,679,025 | 228 |
| 2,679,027 | 188 |
| 2,679,041 | 316 |
| 2,679,042 | 316 |
| 2,679,106 | 68, 444 |
| 2,679,157 | 496 |
| 2,679,159[a] | 88 |
| 2,679,161[a] | 100 |
| 2,679,162 | 148, 16 |
| 2,679,182[a] | 148, 508 |
| 2,679,184 | 196 |
| 2,679,185 | 196 |
| 2,679,205[a] | 360, 136 |
| 2,679,356 | 68 |
| 2,679,366 | 68, 16 |
| 2,679,609 | 308 |
| 2,679,636[a] | 352, 68 |
| 2,679,638 | 68 |
| 2,679,639 | 68 |
| 2,679,642 | 200 |
| 2,679,746 | 288 |
| 2,679,750 | 496 |
| 2,679,755 | 428 |
| 2,679,757[a] | 516 |
| 2,679,898 | 48 |
| 2,679,899 | 48 |
| 2,679,975 | 68 |
| 2,679,976 | 68 |
| 2,680,054 | 324 |
| 2,680,055 | 324 |
| 2,680,156 | 224 |
| 2,680,201[a] | 304 |
| 2,680,226[a] | 132 |
| 2,680,228 | 12 |
| 2,680,238 | 108 |
| 2,680,371 | 188 |
| 2,680,372 | 140, 12 |
| 2,680,373 | 428 |
| 2,680,376 | 288 |
| 2,680,406 | 48 |
| 2,680,613 | 224 |
| 2,680,787 | 484 |
| 2,680,812 | 236 |
| 2,680,819 | 68 |
| 2,680,833[a] | 84 |
| 2,680,900 | 140, 308 |
| 2,680,913[a] | 44 |
| 2,680,989 | 416 |
| 2,681,264 | 324 |
| 2,681,309 | 324 |
| 2,681,387 | 224 |
| 2,681,415 | 168 |
| 2,681,416 | 308 |
| 2,681,419 | 380 |
| 2,681,442[a] | 8 |
| 2,681,565 | 428 |
| 2,681,567[a] | 516, 208 |
| 2,681,570 | 200 |
| 2,681,572 | 188 |
| 2,681,575 | 288 |
| 2,681,576 | 16 |
| 2,681,764 | 312, 68 |
| 2,681,950 | 224 |
| 2,681,952 | 68 |
| 2,681,987 | 316 |
| 2,682,000 | 308 |
| 2,682,001 | 308 |
| 2,682,003 | 4 |
| 2,682,026 | 200 |
| 2,682,041 | 484 |
| 2,682,045 | 68, 444 |
| 2,682,048 | 316 |
| 2,682,049 | 312 |
| Re.23,844 | 200 |
| 2,682,115 | 16 |
| 2,682,170 | 428 |
| 2,682,366 | 68 |
| 2,682,410 | 224 |
| 2,682,578 | 224 |
| 2,682,579 | 484 |
| 2,682,607 | 68 |
| 2,682,657 | 316 |

# REVIEWS

## REVIEWS COMMITTEE

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## CONTENTS

An Introduction to Probability Theory and Its Application, William Feller, by *W. Jacque Yost*. 831
Introduction to Experimental Physics, William B. Fretter, by *Paul Wuenschel*..... 832
An Analogue Computer for Solving Linear Simultaneous Equations, Dušan Mitrović and Rajko Tomović, by *Thomas A. Elkins*..... 833
Gravimétrie à Madagascar; Interprétation Tectonique dans le Sud et l'Ouest (Gravimetry in Madagascar; Tectonic Interpretation in the South and the West), Father Louis Cattala, by *Thomas A. Elkins*..... 834
Geochemical Prospecting at Cobalt, Ontario, G. F. Koehler, P. B. Hostetler and H. D. Holland, by *Paul Wuenschel*..... 834
Present Status of the Lead Method of Age Determination, J. Laurence Kulp, George L. Bates, and Wallace S. Broecker, by *Paul Wuenschel*..... 835
International Scientific Action: The International Geophysical Year 1957–58, L. V. Berkner, by *Nelson C. Steenland*..... 835
Quantitative Studies Concerning the Vertical Gradient and Second Derivative Methods of Gravity Interpretation, Otto Rosenbach, by *Nelson C. Steenland*..... 836
Koninklijk Nederlands Meteorologisch Instituut, 1854–1954, by *Milton B. Dobrin*..... 837
Heat Conduction with Engineering, Geological, and Other Applications, Revised Ed., Leonard R. Ingersoll, Otto J. Zobel, and Alfred Ingersoll, by *Milton B. Dobrin*..... 837
Tables of Lagrangian Coefficients for Sexagesimal Interpolation, National Bureau of Standards Applied Mathematics Series No. 35, by *W. Jacque Yost*..... 838
A Process of Seismic Reflection Interpretation," J. G. Hagedoorn, by *W. Jacque Yost*..... 838

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*An Introduction to Probability Theory and Its Application*, by William Feller, John Wiley and Sons, New York, 1950. $6.50.

Most geophysical workers are required, at some time during their work, to make use of probability theory. When such demands arise, there is often a real problem to find a suitable reference which presents the basic mathematical assumptions involved, the most recent ideas in probability theory, and adequate methods for their application. In such instances, it is difficult to imagine a more suitable book than the present one by Feller. The author has not directed himself specifically to geophysical problems; yet, the great wealth of applications discussed and the clarity in their presentation make the task of using the mathematical material in a particular problem very easy. At the same time, this book is so complete and rigorous in its mathematical sections that the user can avoid the dangers of applying mathematical procedures to non-suitable problems.

The mathematical aspects of Feller's book have been adequately reviewed in the *Bull. Am.*

*Math. Soc.*—Vol. 57, p. 156 (3/51); in the *Am. Math. Monthly*—Vol. 59, p. 265 (4/52); and in the *Math. Reviews*—Vol. 12, p. 424 (6/51). The author's treatment of the basic distribution functions—binomial, Poisson, and normal—is as complete as can be found in any such text. This reviewer has found the section on conditional probability and statistical independence very valuable in many applications to geophysical problems. The latter sections, dealing with random walks, Markov chains, and simple stochastic processes, contain considerable original work by the author and, hence, provide more stimulation to the reader than might otherwise be obtained.

There are two recommendable features of this book for the geophysicist not specifically trained in probability theory. These are Feller's introduction of basic concepts and definitions and his excellent use of applications as illustrations of the theory. All concepts are introduced from the intuitive viewpoint. They are then discussed and illustrated before being stated in the form necessary for the analytical development of the theory. Each significant result of the analysis is then illustrated by well-chosen applications. In most cases, these are used to clarify the analytical results, to extend the analysis somewhat, and to illustrate a general type of application. The author's success in the last-mentioned phase is what makes this book a valuable reference for the geophysicist.

W. JACQUE YOST

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*Introduction to Experimental Physics*, by William B. Fretter, Prentice-Hall, Inc., New York, 1954. 349 pp., $9.00.

The author of this book introduces the graduate student in physics to the techniques and tools used for experiments in modern physics. The coverage of the subject is limited mainly to those techniques developed at, or in use at, the University of California. The tools that are discussed are: particle accelerators such as the Van de Graaff electrostatic accelerator; linear accelerators; cyclotrons; synchrocyclotrons; circular electron accelerators, such as the betatron and synchrotron; and instrumentation for spectroscopy, which includes mass spectroscopy, beta-ray spectroscopy, optical spectroscopy, micro-wave spectroscopy, and, in addition, X-ray diffraction. The author follows a pattern of first presenting the physical principles and the uses of each device, then of describing the instrumentation. He subdivides the entire apparatus into its fundamental parts and discusses each part in detail. Frequently when there are several types of instruments available that are used to accomplish the same goal, the author thoroughly discusses each and presents its advantages and disadvantages. Finally, the operation of one or more of the types of instruments used in each field of investigation is discussed in detail. Helpful hints and precautions on the use of the apparatus are emphasized.

In addition, techniques used in cosmic ray research, molecular beam research, magnetic resonance, pile operation and low temperature physics are discussed along with a review of the present status of each field.

After a brief introduction to the elements of electronics, which includes a section on oscillators and power supplies, the author discusses various amplifiers, stressing the uses to which they are put and their limitations. Waveform generation is discussed and methods of measuring small and large voltages and currents are presented. The techniques of magnetic measurement by other means than magnetron and ballistic galvanometer are presented in detail.

Considerable space is devoted to the design of permanent magnets and electromagnets, and to vacuum techniques. Under the latter topic, the author describes pumping procedures in various pressure regions, the types of pumps available, and the various methods of measuring pressure, and he concludes the discussion with a description of leak-hunting methods.

The discussion of particle detectors is very complete. The author covers ionization chambers, proportional counters, Geiger counters, scintillation counters, nuclear emulsions, and cloud chambers. Not only are their physical principles, methods of construction, uses and operations discussed; but the author is very meticulous in anticipating typical troubles to be encountered in the use of these tools and generously suggests remedies.

Laboratory hazards, not only from radiation but also electrical and mechanical, are indicated and precautions are recommended.

The final chapter discusses "Design of Experiments." The author recognizes two types of experiments in physics, those devoted to conducting a precise measurement and those of an exploratory nature. He cites examples from classic investigations to illustrate each type. Among the personal qualities of an investigator, he believes that the alert and questioning mind that views existing laws critically is the most essential. In designing experiments, he feels that it is necessary to specify the scope of an experiment. He defines scope as being "the ranges or magnitudes over which effects may be observed and reliable information may be gathered." One must "be able to define clearly the scope in advance in order to determine those areas adjoining but lying outside the scope that are not explored."

Taken as a whole, the book is well worth having if the reader wishes to review some of the current experimental techniques concisely and to learn something about the tools used in various specific fields of research. The author frequently becomes so specific in his discussion that he recommends components by manufacturer and model number.

The style in which the book is written is readable and concise, with little repetition. References are always given wherever a subject is not developed completely in the text.

PAUL WUENSCHEL

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"An Analogue Computer for Solving Linear Simultaneous Equations," by Dušan Mitrović and Rajko Tomović. *Recueil de Travaux de l'Institut de Recherches sur la Structure de la Matière*, Belgrade, January, 1953, vol. 2, pp. 5–11.

This paper is being reviewed here for two reasons. The first is that it appears in a journal relatively unknown in the United States. The second is the increasing importance of machine methods of calculation in present-day science, a subject to which the authors hope to make a contribution.

The solution of simultaneous linear algebraic equations is necessary in many problems of pure and applied geophysics; one need only mention the least squares equations which arise in the adjustment of level or gravity networks. The object of the authors was to build an analog computer to handle the maximum number of linear equations for which it would be economical to solve by analog methods.

The least squares principle used in this machine will be briefly explained. Consider the system of linear algebraic equations with real coefficients

$$\sum_{k=1}^{n} a_{ik}x_k - b_i = 0 \qquad i = 1, 2, \cdots, n.$$

An arbitrary set of values $x_k'$ is chosen initially. This set will in general not satisfy the equations and the errors will be

$$\sum_{k=1}^{n} a_{ik}x_k' - b_i = d_i \qquad i = 1, 2, \cdots, n.$$

The least squares method is as follows. The value of $x_1'$ is varied, holding the other $x_i$s'' constant, to obtain the minimum value of $\sum_{i=1}^{n} d_i^2$; next the value of $x_2'$ is varied to obtain a new minimum value for $\sum_{i=1}^{n} d_i^2$, and so on, taking the variables in numerical order and repeating cyclically. If the original set of equations has a non-vanishing determinant, this process will converge, that is, $\sum_{i=1}^{n} d_i^2$ will approach zero and the successive values of the $x_i$s'' will approach the desired solution of the set of equations.

This method is well known but a complication is introduced by the instrumentation used by the authors for their practical realization of the method, a complication which they state does not alter the basic principle fundamentally. Their computer uses alternating current and is essentially an assembly of potentiometers for the multiplications together with amplifiers and rectifiers for the squaring of the errors.

The machine as built will solve as many as thirty simultaneous linear equations; thus, to the best of this reviewer's knowledge, it has the greatest capacity of any analog computer so far built specifi-

cally for this purpose. The authors express no opinion as to the practicability of machines with a greater capacity. Tests were made on the dependence of the precision of the solutions upon the number of equations by solving systems of 4, 10, 20, and 30 equations. In all cases the errors were about 2 percent. The machine is also said to be adapted for use with the well-known Gauss-Seidel iteration method of solving systems of linear algebraic equations, but no details of such use are given.

THOMAS A. ELKINS

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"Gravimétrie à Madagascar; Interprétation Tectonique dans le Sud et l'Ouest (Gravimetry in Madagascar; Tectonic Interpretation in the South and the West)," by Father Louis Cattala, *Travaux du Bureau Géologique de Madagascar*, Numéro 59, Service Géologique, Tananarive, 1954. i+7 pages, 4 figures, 2 separate maps.

Since 1948 gravity measurements have been made in Madagascar with a North American gravimeter. A tie of the Madagascar network to the European network was made in 1951 with another North American gravimeter. At present there are about a thousand stations and others are projected. The stations are made along trails accessible by jeep, with a station spacing of about fifteen kilometers. This method leaves large areas without stations. In the south the accuracy is estimated at some tenths of a milligal; in the other areas it may exceed a milligal.

Two separate maps are included, a contour map of the Bouguer anomalies and a map giving the tectonic interpretation of the gravity results.

The interpretation is based on a study of a plot of the Bouguer anomalies as ordinates against the altitudes as abscissas. If isostatic compensation were perfect, the points would tend to cluster near a straight line through the origin with a definite known slope. If we consider all the points, the expected slope is found, but the straight line does not go through the origin and is shifted upward in the positive direction. This variation from perfect isostasy is ascribed to lateral compressive forces. Actually the slopes of some of the traverses differ from the expected slope value. Also, most of the straight lines do not pass through the origin but are shifted up or down. An upward or downward shift is considered to indicate, respectively, an upward or downward crustal movement. The boundaries of the regional geologic units are deduced in this fashion. These boundaries are believed in most cases to be faults.

In areas where checks against geologic data were available, this method gave concordant results. It is emphasized by the author that the interpretation is tentative, one reason given being that topographic corrections were not made. The sparseness and poor spacing of the data should also have been cited since the basic idea of the analysis is statistical, so that the validity of the results depends on the completeness and representativeness of the gravity data.

Bound in with the report is a list of the sixty numbers of the *Travaux du Bureau Géologique de Madagascar* thus far issued, which will be valuable to those interested in the geology of this area.

THOMAS A. ELKINS

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"Geochemical Prospecting at Cobalt, Ontario," by G. F. Koehler, P. B. Hostetler, and H. D. Holland, *Economic Geology*, Vol. 49, No. 4, June–July 1954, p. 378–388.

A geological setting in which geochemical techniques can aid in the exploration for mineralization is described. A thin cover of glacial and lacustrine sediments (0–25 ft thick) overlies basement rocks containing silver, nickel, and cobalt mineralization as mesothermal fissure fillings.

Samples were taken on a horizontal square grid pattern of one-hundred-foot spacing and at one-foot intervals vertically. All samples were analyzed for cobalt by standard techniques.

The dispersion of cobalt about an ore pile indicated that cobalt can be carried vertically by vadose water more easily than horizontally. The effect of the ore pile was not observed more than forty feet from its periphery.

Topography affects the distribution of cobalt in such a way that samples taken on topographic highs are lower in cobalt concentration than those taken on lows. Topographic effects are easily recog-

nized because, like vegetation effects, they cause a rapid decrease in concentration gradients with depth.

An anomaly is identified by an increasing gradient of cobalt concentration with depth from the surface to the bedrock. The anomalies observed, even over non-commercial deposits, were several orders of magnitude above the average value for the overburden.

PAUL WUENSCHEL

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"Present Status of the Lead Method of Age Determination," by J. Laurence Kulp, George L. Bates, and Wallace S. Broecker, *American Journal of Science*, Vol. 252, No. 6, June, 1954, p. 345–365.

The purpose of the paper is to summarize existing data on the lead method of age determination, to examine the errors that arise in using this method, and to discuss its potentialities for the student of the earth sciences.

Prior to Nier's classic work of 1939 in which he determined the isotopic constitution of radiogenic lead, the lead-uranium method for age determination was based on chemical determinations of the lead, uranium, and thorium content of the sample. This value for the age would be in error if "common lead" were present, or if either of the radioactive series were disrupted from equilibrium by such processes as the leaching of uranium or the escape of radon.

The authors review existing data and recalculate ages for various samples using the $Pb^{206}/U_{238}$, $Pb^{207}/U_{235}$, $Pb^{207}/Pb^{206}$, and $Pb^{208}/Th^{232}$ ratios. The four ages calculated for the same sample using these four ratios do not, as a rule, agree. The reason for this disagreement, according to the authors, could be radon leakage, leaching of uranium, or failure to consider the amount of "common lead" present.

The authors then investigate each of these sources of error. By experiment they determined the amount of radon leakage from various uranium minerals as a function of temperature and particle size. Using this evidence they proceed to calculate the error, with respect to age, that would result if the radon leakage were neglected. The same line of reasoning is applied to the leaching of uranium. To study the error caused by neglecting "common lead," they examined 23 samples from diverse localities. The $Pb^{206}$, $Pb^{207}$, and $Pb^{208}$ content relative to that of $Pb^{204}$ varied from one sample to another by not more than $\pm 25$ percent. Samples from a single district varied over a range of only 2 percent. It is possible then from the knowledge of $Pb^{204}$, or $Pb^{208}$ if there is no $Th^{232}$ present, to estimate the amount of "common lead" present and thereby apply a suitable correction.

With these refinements, the authors believe that the lead age measurements will approach an uncertainty as low as 2 percent in the range from 50 million years to 3000 million years.

PAUL WUENSCHEL

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"International Scientific Action: The International Geophysical Year 1957–58," by L. V. Berkner, *Science*, Vol. 119, No. 3096, Apr. 30, 1954, p. 569.

This well written and rather comprehensive article of seven pages first presents the reasons for having a year of international, cooperative scientific investigations, then describes the plans for the forthcoming International Geophysical Year, 1957–58. The author is Vice Chairman, Special Committee on the IGY.

The historical development of the sciences affords ample evidence for the necessity of providing a means for the exchange of ideas among the individual sciences. The science of electromagnetism is given as an example, having been conceived from clues presented by a chemist, a botanist, an evangelist, and a statesman, among others. That an international year is a medium for such an exchange is demonstrated by the results of the first such year in 1883 and those of the second in 1932–33. The effort of 1883 led to the "clarification of our knowledge of geomagnetism" and Fritz's work on auroral phenomena. The second year produced, among other results, the Geophysical Institute of the University of Alaska.

The forthcoming third geophysical year will be organized in "nine general scientific areas: meteorology, longitude and latitude determinations, geomagnetism, the ionosphere, aurora and airglow, solar activity, cosmic rays, glaciology, and oceanography." The activities of the United States are being handled by the National Academy of Sciences through a committee under the chairmanship of Prof. Joseph Kaplan, University of California at Los Angeles. The activities include arrangements for expeditions to remote areas to gather data necessary for the understanding of global phenomena and plans for coordinated observations throughout the world on so-called "World Days."

For example, in the field of meteorology there are theories regarding conditions in Antarctica that may have a profound effect on world weather but upon which there are essentially no relevant data. In the field of geomagnetism, concerted action will be concentrated on the well-known phenomena of magnetic storms and diurnal variation. In geodesy, there will be an effort to connect accurately the surveys on the various continents.

Although the activities of the IGY appear to be only remotely related to commercial geophysics, even a geophysicist with the limited experience of the reviewer can find areas of definite interest. The water operations in the Gulf Coast are a prime example of the need for a much more reliable knowledge of weather forecasting. Also such operations as these require radio-communication between land and water units and between the mobile units themselves. Additional knowledge of anomalous radio-wave transmission would be of economic value. Then, of course, the obvious problems of diurnal variation and magnetic storms in aeromagnetic surveying could well benefit from further understanding. But of importance transcending these commonplace problems in exploration geophysics is the possibility that new knowledge, at present beyond our imagination, may open new pursuits to us. Exploration geophysics can contribute to IGY on its own account. Witness the coordinated effort of several years back in the world-wide gravity program to study earth tides. Our Society and our profession should express its willingness to contribute to IGY. We could very well benefit thereby.

NELSON C. STEENLAND

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"Quantitative Studies Concerning the Vertical Gradient and Second Derivative Methods of Gravity Interpretation," by Otto Rosenbach, *Geophysical Prospecting*, Vol. II, No. 2, June, 1954, pp. 128–138.

Rosenbach's article is interesting because it is one of the few published examples of a quantitative interpretation of derivative gravity data.

The observed gravity data are a survey of the "Worms" Area in the Rhine Graben, Germany, an area somewhat less than 400 sq. km. The density of stations appears to be more than one per sq. km. The western boundary fault of the graben occurs within the area, and a large observed anomaly of tens of milligals is easily identified with it. The purposes of the analysis are to "localize" the main fault within a limited area and to "recognize" minor structures within two additional areas in the graben. The analysis includes (1) vertical gradient according to Baranov, and second vertical derivatives according to (2) Elkins and to (3) Rosenbach.

The three methods are computed by conventional grid template procedures. Only the fault problem is actually analyzed quantitatively. For this, it is assumed that the fault is a simple, inclined plane and that the density-contrast begins at a depth of 200 m. The upper trace of the fault plane, at 200-m depth, is placed under the zero derivative value, a conventional step. The angle of the plane is derived from the ratio of the maximum to minimum amplitude. Rosenbach recognizes the distortions given to the peaks and extremities of derivative values by grid calculations but he professes to be able to recognize these, apparently by comparisons with theoretical curves. In light of the assumptions regarding the subsurface and in view of the recourse to theoretical curves, it is inconceivable to use derivative methods when the analysis could be made much more accurately and quickly from the observed data.

The discussions of the two remaining areas purport to criticize the Elkins' formula because in some instances it develops only one anomaly where two subsurface structures are known. On the other hand, the Baranov and Rosenbach methods yield two anomalies. Rosenbach recognizes that

the apparent deficiency of Elkins' formula could be corrected by using a smaller grid spacing. In other words, the Elkins' coefficients emphasize values of greater distance from the center point than do the other two. It would have been better to have made this correction than to leave the inference that formulae of European origin are more successful on European problems.

NELSON C. STEENLAND

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*Koninklijk Nederlands Meteorologisch Instituut, 1854–1954*, The Hague, Staatsdrukkerij- en Uitgeverijbedrijf, 1954.

One of the most outstanding scientific institutions in the world, The Koninklijk Nederlands Meteorologisch Instituut (Royal Dutch Meteorological Institute) celebrates its 100th anniversary this year. In commemoration of this event, the Institute has published a beautiful and impressive volume, 470 pages long, which fittingly records its history and outstanding accomplishments during this period. In its century of existence, this institution has been responsible for very important contributions to a multitude of fields in the earth sciences. These contributions have been not only to meteorology, but also to oceanography, seismology, geomagnetism, and other branches of geophysics. Many of its directors—and other members of its staff during the hundred years of its existence—have been scientists who were distinguished not only in the Netherlands but all over the world. Among these have been Van der Walls (originator of the equation known to every student in elementary chemistry), Kamerlingh Onnes, Vening Meinesz, and Buys Ballot. The Institute has issued more than 200 publications dealing with many branches of science.

In this day of high printing costs, it is seldom that one sees as craftsmanlike a specimen of book manufacturing as this volume. The paper and binding are both of fine quality. The color reproductions, mostly illustrating various types of cloud formations over the ocean, are excellent; and the printing and composition show first-class skill. The text is in Dutch; however, even those readers who are not familiar with this language (such as the reviewer) should find perusal of the volume enjoyable. The photographs and diagrams are in themselves highly communicative and enough words in Dutch are similar to corresponding words in English and German, that it should not be difficult for someone reasonably familiar with both languages to get the drift of the material.

The first part of the volume covers the history of the Institute in some detail. The second part describes the facilities, equipment, and special instrumentation which the Institute uses in the course of its work and gives a summary of the various projects now in progress. One of the chapters in this part is entitled "Geophysics." In this chapter there are sections on earth magnetism, giving sample records recorded at the Institute's magnetic observatory; seismology, describing the Institute's seismological observatory and presenting one of its sample earthquake records; and investigation of the ionosphere, presenting some samples of the studies in this field. The final section contains a collection of original papers on various phases of meteorology and other branches of geophysics written by members of the Institute's staff. This section is about 170 pages long. Most of the papers are on meteorology or oceanography, although one is on seismology. All are in Dutch with English abstracts. The paper on seismology is entitled "Microseismen" (Microseisms) by J. G. Scholte; it is primarily mathematical.

The Institute can well be proud of its scientific accomplishments during its first century. We on this side of the Atlantic extend our felicitations and our best wishes for a second century of equally noteworthy accomplishment.

MILTON B. DOBRIN

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*Heat Conduction with Engineering, Geological, and Other Applications*, Revised Ed., by Leonard R. Ingersoll, Otto J. Zobel, and Alfred Ingersoll, The University of Wisconsin Press, Madison, Wisconsin, 1954, $5.00.

About thirty years ago, Leonard R. Ingersoll and Otto J. Zobel published a text book on heat conduction which was widely used by physics and engineering students as an introduction to the mathematical methods by which problems on heat flow and related topics might be solved. In 1948,

the two original authors and the son of the senior author collaborated to prepare a second edition which included many applications of heat flow to geological problems. The latest publication, labeled "Revised Edition" although it is actually the third edition, is very much like the second except for the fact that two new chapters have been added, both on subjects of considerable current interest. One of these chapters is entitled "Theory of Earth Heat Exchangers for the Heat Pump" and the other, "Drying; Soil Consolidation."

The chapter on heat pumps will be particularly welcomed by those of us who have been curious about the recent spurt of activity in the manufacture of these double-purpose units, which keep buildings warm in winter by removing heat from cold air or cold earth, and which can be reversed with the turning of a valve to cool them in the summer by removing heat from them and depositing it in the air or the earth. Although the principle of such devices was discovered by Lord Kelvin about 100 years ago, it is only in the last few years that the large manufacturers of electrical and air-conditioning equipment have begun to put them into large-scale production.

To enumerate the applications of heat flow to geology discussed in the book, the following section headings, taken from a number of chapters, are quoted: Subterranean Temperature Sinks and Power Development; Geysers; Thawing of Frozen Soil; Cooling of Lava Under Water; Cooling of the Earth, with and without Radioactive Considerations and Estimates of Its Age; Temperatures in Decomposing Granites; Ground Temperature Fluctuations and Cold Waves; Postglacial Time Calculations; Terrestrial Temperatures; Water Movement in Soil; Theory of Soil Consolidation; and Application of Heat Conduction Equations to Consolidation.

The book makes use of the conventional mathematical tools, such as Fourier series and Bessel functions, which give solutions to the heat flow equation. The presentation is well adapted for the student with limited training in advanced mathematics and the authors have taken pains to relate the mathematical formulae to numerical examples and graphical presentations of results.

MILTON B. DOBRIN

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*Tables of Lagrangian Coefficients for Sexagesimal Interpolation*, National Bureau of Standards Applied Mathematics Series No. 35, Washington, D. C., Jan., 1954.

Those geophysical workers who have need to interpolate functions which are tabulated in degrees (or hours), minutes and seconds will welcome this volume as a great time saver. Previously any Lagrangian interpolation (which is becoming more widely used as automatic or desk calculators are used) had to be performed by a rather cumbersome double interpolation process. This present volume tabulates the coefficients directly for a sexagesimal system and hence eliminates such a cumbersome procedure. Previous tabulations in this system have only been fragmentary. The present volume lists the coefficients for three-, four-, five-, and six-point interpolation, which should be sufficient for nearly all applications. The coefficients are given to eight decimals and are very conveniently tabulated.

W. JACQUE YOST

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"A Process of Seismic Reflection Interpretation," by J. G. Hagedoorn, *Geophysical Prospecting*, Vol. 2, no. 2, 1954, p. 85–127.

This complete reproduction of Hagedoorn's thesis at the University of Utrecht, Holland, should make more readily available an excellent contribution which might otherwise have had a limited circulation. The clarity of the writing, the excellence of the many line drawings, and the simplicity of the expository style make this a pleasure to read. Since, in addition, the thesis contains novel and sound technical developments which appear to be readily applicable to many practical problems, all of the elements are present for a worthwhile addition to the literature of seismic interpretation. Beyond these statements, this reviewer would not attempt to evaluate the significance of Hagedoorn's work. This must be done by those readers who can make use of the author's developments and thus test the ideas in practice. Hence, the following summary is intended only to arouse interest in enough readers to that such an evaluation will be accelerated.

Hagedoorn's basic point of departure is that "it is quite impossible to speak of trajectories in a physical sense of narrow beams" for the usual seismic exploration case. Instead, he prefers to base his interpretation on the concept of wave fronts. He then sets for himself the problem of developing techniques which will simplify the practical use of such a concept. The method of vertical plotting and subsequent migration to locate true reflecting surfaces is used as a starting point since it is generally valid for profiles along lines of maximum dip. Any surface which contains all possible reflecting points for a given reflection time, a given shot, and a given receiver is called a surface of equal reflection. These are, in general, surfaces which are more concave than any real reflecting surface. From these ideas, the author introduces the concept of surfaces of maximum convexity. The bulk of his paper then consists of detailed instructions and charts for using these ideas to locate reflecting surfaces with greater precision.

The difficulties encountered in routine interpretation of seismic work are frequently related to the inability to use a reasonable velocity-vs.-depth function with sufficient speed. While Hagedoorn's methods are just as cumbersome for complicated velocity-vs.-depth as ray-tracing techniques, they are no more so. Furthermore, he gives a good discussion of how to choose a workable approximation from the known, real function. The two types of approximations for which detailed interpretation charts are given are: (1) velocity a linear function of depth; and (2) velocity a linear function of vertical travel time. In the final section of this thesis, the author shows how it is possible to use a master set of wave-front charts with different scaling factors. This eliminates the need for preparing a wide variety of charts for each computational problem.

Finally, this reviewer would like to point out that the excellent typography, the clarity of the drawings, and the apparently error-free reproduction are a tribute to all those concerned with the reproduction of this thesis.

W. JACQUE YOST

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## PUBLICATIONS RECEIVED

*American Journal of Science*, v. 252, nos. 5, 6 & 7 (May, June & July, 1954)
*Annales de Geophysique*, v. 10, no. 1 (Jan. & March, 1954)
*Annali di Geofisica*, v. 6, no. 4 (October, 1953)
*Boletin de la Asociacion Mexicana de Geologos Petroleros*, v. 6, no. 3–4 (March–April, 1954)
*Bulletin Géodésique*, no. 32 (June 1, 1954)
*Bulletin of the Seismological Society of America*, v. 44, nos. 2 & 2B (April, 1954)
*Canadian Geophysical Bulletin*, v. 6 (December, 1953)
*Economic Geology*, v. 49, nos. 3 & 4 (May & June–July, 1954)
*Erdöl und Kohle*, v. 7, nos. 4, 5 & 6 (April, May & June, 1954)
*Geological Abstracts*, v. 11, no. 2 (1954)
*Journal of Geophysical Research*, v. 59, no. 2 (June, 1954)
*Precambrian*, v. 27, nos 4 & 5 (April & May, 1954)
*Quarterly Journal of the Geological Society of London*, v. 109, nos. 3 & 4 (April 28 & June 3, 1954)
*Revista di Geofisica Applicata*, v. 14, no. 2 (1953)
*Science*, v. 119, nos. 3097–3104; v. 120, nos. 3105–3108 (May 7–July 27, 1954)
*Science Reports of the Tohoku University*, 5th Series, Geophysics, v. 5, no. 2 (October, 1953)
*Scientific Monthly*, v. 78, no. 6 (July, 1954); v. 79, nos. 1 & 2 (July & August, 1954)
*Tellus*, v. 6, no. 1 (February, 1954)
*Transactions and Proceedings of the Geological Society of South Africa*, v. 54 (1953)

### NEW BOOKS RECEIVED

Bruckshaw, J. McG., 1954, Magnetic variometers: London, Hilger & Watts Ltd.
Bullen, K. E., 1954, Seismology: New York, John Wiley & Sons, Inc.
Davis, W. M., 1954, Geographical essays: New York, Dover Publications, Inc.

GEOPHYSICS, VOL. XIX, NO. 4 (OCTOBER, 1954), PP. 840–843, 2 FIGS.

# MEMORIAL

DAVID M. WEBER

David M. Weber, Seismic Interpretation Section Head at Gulf Research & Development Company died June 9, 1954, at the Presbyterian Hospital in Pittsburgh. He is survived by his widow, Mrs. Violet Tierney McCormick Weber; a stepdaughter, Barbara Ann McCormick, aged 17; and by two children, Joan, aged 9, and David, Jr., aged 6.

Dave was born April 24, 1915, to Arthur C. Weber and Addie M. Weber at Inogomar, Pennsylvania, near Pittsburgh. He was educated in the local public schools. Because of the need to earn his living, his further education was mostly on a part-time basis with several long interruptions. He first entered the University of Pittsburgh in 1933. He received his degree in 1941.

In 1937 he first entered the field of geophysics. In May of that year he was employed as a junior observer by the National Geophysical Company. He was sent to Cuba a year later as observer on a crew working for the Atlantic Refining Company. At the conclusion of the project in May, 1939, he decided to return to Pittsburgh to continue his education. In January, 1940, he was employed by the

Geophysics Division of the Gulf Research & Development Company and assigned to seismograph interpretation.

It soon became apparent that Dave had a natural flair for seismic interpretation and in November, 1942 he was sent to Venezuela to interpret the data obtained by a crew working for Mene Grande Oil Company. He returned to the United States in 1944 and in August of that year he was assigned to a crew in Mississippi. A year later he became party chief on a crew working in West Texas. In March, 1946, he was transferred again to Venezuela where he remained until March, 1948. His next assignment was back at the Laboratory in Pittsburgh where he remained until his death.

In 1950 he was made a seismic section head and was placed in charge of a group of interpreters specializing on data from western Canada.

Dave Weber was certainly a success as a seismologist and just as certainly his early death cut short a career in which he would have gone far. He brought to his job a complete kit of tools. He had sound fundamental training and a sharp inquisitive mind. He was one of that rare breed who get ideas—by flashes of inspiration, perhaps, or perhaps by concentration on the problems at hand and orderly habits of thinking. He attacked seismic problems by bringing together every bit of evidence he could find, geological and geophysical. He was adept at getting information from others. People liked to talk to him. They caught something of his enthusiasm, they did a little thinking, they came up with ideas. He had the gift of clear exposition and he inspired confidence in his work because he had the self-confidence of the true professional. But confidence never degenerated into complacency with Dave. He was not happy with a job as long as he had failed to clean up those unexplained little discrepancies that often turned out to be the key to the problem.

In his supervisory position in recent years he was beset by the problems of rapid expansion in geophysical activity. He worked under almost constant pressure but he was always equal to the demands made on him and he never lost his even-tempered cheerfulness. His staff was composed for the most part of promising but relatively inexperienced younger men. Under Dave the teacher they progressed rapidly. He encouraged them to think. He challenged them by giving them responsibility to the measure of their capacity. He gave them recognition for work well done. He was always a counselor and friend.

As a personality he was outstanding. He was a devoted husband and father. He was a sought-after social companion because his friendliness was warm and genuine. His own ethical standards were of the highest but he was patient with weakness in others. His courage was demonstrated in those last months when he must have known what was in store for him. His countenance remained smiling. His talk was of future plans. He never gave up fighting until the final day or two of merciful unconsciousness.

Dave Weber's death is a loss not only to his family and friends but to the company and the profession he so capably served.

T. J. O'DONNELL

# MEMORIAL

HUBERT LÜCKERATH

Dr. Hubert Lückerath, a member of the Society, died in Hannover, Germany, on April 12, 1954 after having been ill for a long time. In his death the profession of applied geophysics in Germany has lost one of its pioneers, not only with regard to seismic prospecting in general and other geophysical methods but particularly in the field of seismic reflection work.

Born in 1896, Dr. Lückerath pursued his university training in physics in Cologne and Bonn, Germany, from 1916 to 1921 where he was awarded the degree of Ph.D. He became interested in the then approaching application of geophysics to geological problems and entered the Erda Co., Göttingen, for which company he was mainly engaged in geoelectrical and magnetic research work in Germany and southern Europe. After the merger of Erda with Seismos Co., Hannover, in 1925, he was chiefly employed in seismic investigations and took part in the exploration campaign of Prof. Dr. Mintrop in various parts of the U. S. A.

With the development of reflection seismics by Seismos Co., Dr. Lückerath,

in co-operation with Dr. Fr. Trappe, applied appropriate instruments and field methods to this line of work. In 1933 he was party chief of the first regular reflection seismic survey carried out in Germany. After having been in charge of the reflection seismic department of Seismos Co. from 1938 to 1949, in acknowledgment of his clear-sighted and circumspect work, he became chief manager of that company. It is especially due to him that after the break-down following the second World War geophysical surveying could effectively be applied again with instruments brought up to a high standard. His standing and personality, together with a wide experience in his profession, guaranteed the success of the investigations he carried out in oil, coal, and ore mining districts of Germany and elsewhere in Northwest Europe.

Although serious-minded with regard to his work, he possessed thoughtfulness and consideration for others. His earnest straight-forward nature tempered with a quiet sense of Rhenish humor won him the respect and friendship of all who knew him.

TH. H. KREY

# CONTRIBUTORS

KENNETH L. COOK

KENNETH L. COOK received a B.S. degree in Physics in 1939 from the Massachusetts Institute of Technology and a Ph.D. degree in Geology and Physics in 1943 from the University of Chicago. At the University of Chicago he was engaged in part-time teaching duties as a University Fellow during 1939–41 and Instructor during 1941–43.

Since 1943 Dr. Cook has been actively engaged in geophysical field work as geophysicist in the Division of Geophysical Exploration of the U. S. Bureau of Mines (1943–1946) and in the Geophysics Branch of the U. S. Geological Survey (1946 to present). This field work has comprised chiefly strategic-mineral investigations in mining districts of the West and Midwest for iron, copper, lead, zinc, and salt, in which he has employed magnetic, gravitational, electrical (surface and well-logging), and seismic surveys as guides in the exploration. He has also made regional gravity surveys in eastern Maryland, northeastern Oklahoma, and southeastern Kansas.

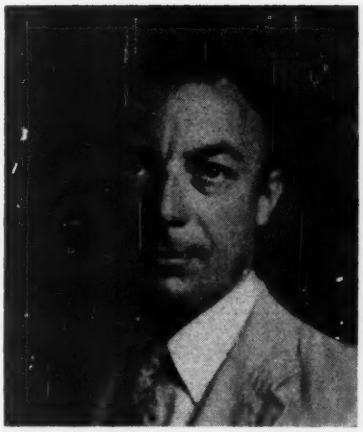
In 1953 Dr. Cook was appointed Associate Professor and Head of the Department of Geophysics, University of Utah, Salt Lake City, Utah. He continues his affiliation with the U. S. Geological Survey on a part-time basis for research studies in geophysics.

Dr. Cook has served the Society of Exploration Geophysicists as a member of the Reviews Committee from 1949 to 1953 and is at present a member of the Committee for the Mining Geophysics Case History Volume. He indexed the technical papers and reviews in GEOPHYSICS for the revised Cumulative Index of the Society of Exploration Geophysicists, scheduled for publication during 1954. He is a member of the American Geophysical Union, American Institute of Mining and Metallurgical Engineers (a member of the Executive Committee of the Mining, Geology, and Geophysics Division; and Acting Chairman of the Geophysics Subdivision), Geological Society of America, Sigma Xi, Society of Exploration Geophysicists, and Utah Geological Society.

CHARLES HEWITT DIX

CHARLES HEWITT DIX received his B.S. degree in Physics from the California Institute of Technology in 1927, and his Ph.D. in Mathematics from the Rice Institute in 1931. He was an instructor in Mathematics at Rice from 1929 until 1934, when he became associated with the Humble Oil & Refining Company as a research geophysicist. In 1939 he became geophysicist for the Socony-Vacuum Oil Company, handling the research aspects of foreign geophysical exploration.

In 1941 he joined United Geophysical Company as Chief Seismologist. A year later he became Vice President and a Director of the company. At the end of 1947 he resigned to become Associate Professor of Geophysics at the California Institute of Technology. He became Professor of Geophysics at Caltech this year. He is the author of a book on seismic prospecting and of fifteen papers on geophysical and mathematical subjects. He is a member of the Society of Exploration Geophysicists, The American Association of Petroleum Geologists, American Geophysical Union, Seismological Society of America, and the American Physical Society.



WILLIAM L. DONN

WILLIAM L. DONN is a native New Yorker who received his B.A. at Brooklyn College in 1939 and Ph.D. at Columbia University, 1951. His time has been divided between teaching and research, the former with the Department of Geology at Brooklyn College (since 1946), and the latter work as Research Associate of Columbia University (Lamont Geological Observatory) since 1951. His principal research has involved study of oscillations of the ocean and atmosphere and microseisms. Past professional experience includes: Geologist, Delaware Aqueduct Project; Geologist, U. S. Engineers; Research Consultant, Woods Hole Oceanographic Institution; Lieut. USNR (1942–46) with duty as Head of Meteorology Department at the U. S. Merchant Marine Academy and Aerologist, Naval Air Navigation School.

He is a Fellow of the Geological Society of America; Professional member of the American Meteorological Society; Member of N. Y. Academy of Sciences and Chairman of its Section of Oceanography and Meteorology (1950–52); Member of Seismological Society of America, American Geophysical Union, A.A.A.S., and the Society of Sigma Xi. He is author of numerous scientific papers and the textbook, "Meteorology—with Marine Applications."

HAL J. JONES

HAL J. JONES received undergraduate training in geology and mathematics at DePauw University and at Louisiana State where he received a B.S. degree in 1945. During 1945–46 and 1948 he pursued graduate studies in geophysics at the California Institute of Technology. He received an M.S. in geology at the University of Cincinnati in 1947 and the Ph.D. degree in geology at the University of Texas in 1950. During 1947–48 and 1950 he worked as a geologist and geophysicist for Shell Oil Company. In 1951 he served as a physicist and research group head for Engineering Research Associates, working in Utah on underground explosion studies connected with bomb shelter design. During 1952 he was employed by Stanolind Oil and Gas Company as technical supervisor of a field research crew. In December 1952 he joined Texas Instruments Incorporated, Dallas, and at present is Director of Geophysical Research.

PHILIP L. LAWRENCE

PHILIP L. LAWRENCE was born in New Bedford, Massachusetts in 1923. He entered the Colorado School of Mines in 1941, served from 1943 to 1946 in the U. S. Army, and received his Geological Engineer's degree from C. S. M. in 1949, majoring in geophysics. After a brief period of employment as a seismic computer with the Shell Oil Company, he joined the Field Research Laboratories of the Magnolia Petroleum Company in 1949. For two years, he performed various duties on an experimental field party, and has since been engaged in seismic research activities at the Laboratories. Mr. Lawrence is a member of the Society of Exploration Geophysicists, the American Geophysical Union, the Seismological Society of America, and is an associate member of The American Association of Petroleum Geologists.

ÖRNULF LOGN received his Cand. Real. degree (Corresponding to Master of Science) from the Oslo University, Norway, in 1946.

Since 1944 he has been engaged in geophysical field work with the Geofysisk Malmleting, Trondheim, Norway (the Norwegian Institute of Geophysical Exploration), the first year as party assistant, later as party chief in electromagnetic, geoelectric, and magnetic prospecting.

From 1952 to 1954 he was on leave from the Geofysisk Malmleting, having a teaching fellowship at the Norwegian Institute of Technology, Geological Department, in Trondheim. Since the summer of 1954 he has been with the Geofysisk Malmleting.

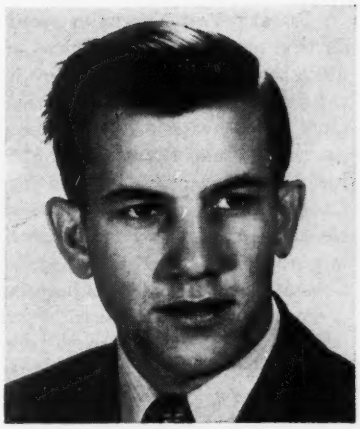
He is a member of Norsk Geologisk Forening (Norwegian Geological Society).

ÖRNULF LOGN

HOLLAND C. MCCARVER

HOLLAND C. MCCARVER attended the University of Texas from 1931 to 1937, majoring first in business administration and then in geology. He was employed in 1937 by Geophysical Service Inc., and remained with that company until January 1944 when he joined the Seaboard Oil Company as Chief Geophysicist. In 1954 Mr. McCarver was promoted to Manager of Geological and Geophysical Departments. He is a member of the Society of Exploration Geophysicists, The American Association of Petroleum Geologists, the Dallas Geological Society, and the Dallas Geophysical Society.

JOHN A. MORRISON, JR. received a B.S. in E.E. from Southern Methodist University in March 1951. Upon graduation he joined the Vitro Corporation of America, Silver Spring, Maryland laboratory, where he was engaged in the design and execution of metering apparatus to measure the performance of underwater ordnance vehicles. He joined Texas Instruments Incorporated in September 1952, and is currently working on the design of electrical circuits appropriate to solution of seismic correlation problems.



JOHN A. MORRISON, JR.

BEN F. RUMMERFIELD

BEN F. RUMMERFIELD was graduated from Colorado School of Mines in 1940 with a degree of Geological Engineer, having majored in geophysics. He was employed by Seismograph Service Corporation as a rodman and advanced to seismic party chief, working in a major portion of the geological provinces of the United States.

In 1944 Mr. Rummerfield went to Venezuela in the capacity of seismic supervisor. He returned to the United States in the fall of 1947 and completed the Advanced Management Program at the Harvard Graduate Business School in 1947. He was then transferred to Mexico, where he worked for three years as Assistant Manager and seismic supervisor.

Mr. Rummerfield joined Century Geophysical Corporation in July, 1950, as manager of seismic operations in the United States and Canada. In October, 1951, he was appointed Vice-President and a member of the Board of Directors of Century Geophysical Corporation, which positions he now holds. He is also Executive Vice-President of Century Geophysical Corporation of Canada and Century Drilling Corporation.

He is a member of the SEG, AAPG, American Geophysical Union, Geophysical Society of Tulsa, Tulsa Geological Society, Asociacion Mexicana de Geologos Petroleros, Sigma Gamma Epsilon, and Blue Key.

ROBERT VAN NOSTRAND received a B.S. degree in physics from the Missouri School of Mines in 1942 after which he went on duty as an Army Signal Officer. After five years' service, he returned to the same school where he became an Instructor in Physics, also pursuing his graduate studies part time. He received a M.S. degree in physics in 1949. He commenced studies in the University of North Carolina the same year and in September, 1952 he completed his work for the Ph.D. degree in physics with a minor in geology. In October, 1952 he joined the Field Research Laboratories of the Magnolia Petroleum Company where he is directing research in electrical prospecting. During the period from June, 1948 through June 1953, he served as a geophysicist on a part time basis for the U. S. Geological Survey. Professional affiliations include Sigma Xi, Society of Exploration Geophysicists, American Geophysical Union, European Association of Exploration Geophysicists, Dallas Geophysical Society, and Dallas Geological Society.

ROBERT VAN NOSTRAND

N. N. ZIRBEL

N. N. ZIRBEL received the B.A. and M.A. degrees from Rice Institute in 1930 and 1931, respectively. He joined the Independent Exploration Company at its organization in 1932 and is now a geophysicist with that company. He is a member of the Society of Exploration Geophysicists. The American Association of Petroleum Geologists, and the American Geophysical Union.

Biographies and photographs of other authors of papers in this issue have appeared in recent issues of GEOPHYSICS as follows: MILTON B. DOBRIN, v. XVII, p. 992 (October, 1952); MAURICE EWING, v. XIV, p. 595 (October, 1949); CECIL H. GREEN, v. XVIII, p. 726 (July, 1953); FRANK PRESS, v. XIII, p. 489 (July, 1948); RAYMOND L. SENGBUSH, v. XVIII, p. 244 (January, 1953).

# SOCIETY ROUND TABLE

## COMMITTEES

### Executive Committee, Eighteen Months Ending in October, 1955

*President:* Paul L. Lyons, Anchor Petroleum Co., Tulsa, Oklahoma
*Vice-President:* Roy F. Bennett, Sohio Petroleum Co., Oklahoma City, Oklahoma
*Secretary-Treasurer:* Hugh M. Thralls, Seismograph Service Corp., Tulsa, Oklahoma
*Editor:* Milton B. Dobrin, Magnolia Petroleum Co., Dallas, Texas
*Past President:* Roy L. Lay, The Texas Company, New York, N. Y.

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*Chairman:* Roy F. Bennett, Sohio Petroleum Co., Oklahoma City, Oklahoma

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*Arrangements Chairman:* Harvey Cash, The Texas Company, New York, N. Y.

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Curtis H. Johnson ('59)

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Van A. Petty, Jr.
Philip C. Ingalls
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Lewis Riley

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### Special Committee on Geophysical Case Histories Volume II

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*Editor:* Paul L. Lyons, Anchor Petroleum Co., Tulsa, Oklahoma

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| Milton B. Dobrin | John W. Daly | Paul E. Nash |
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| Marvin Romberg | W. H. Fenwick | E. S. Sherar |
| W. W. Newton | C. H. Dresbach | L. L. Nettleton |
| O. C. Clifford | R. M. Bradley | Eugene W. Frowe |
| Dean Walling | W. L. Matjasic | H. C. McCarver |
| R. F. Beers | A. B. Bryan | Roy L. Lay |

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| Cecil H. Green | Sigmund Hammer | L. L. Nettleton |

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| R. A. Peterson | J. E. Hawkins | J. E. White |
| G. M. Grosjean | | |

### Advisory Committee on Radioactive Mineral Exploration

(Joint committee of AAPG, SEPM, and SEG)

F. H. Lahee ('55), *Chm.*, Sun Oil Company, Box 2880, Dallas, Texas

Henry C. Cortes* ('56), *Vice-Chm.*, Magnolia Petroleum Company, Box 900, Dallas, Texas

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|---|---|---|
| John G. Bartram | Gerhard Herzog* | Roland F. Beers* |
| Cecil H. Green* | Robert R. Rieke | Jean C. Finley |
| Morton T. Higgs | Wilfred B. Tapper | Harold N. Fisk |
| J. Harlan Johnson | Gerald H. Westby* | Ronald E. McAdams |
| | | H. E. Stommel* |

### Directors of the American Geological Institute

George E. Wagoner (Nov., 1954) — Sigmund Hammer (Nov., 1955)

### Representative on Division of Earth Sciences National Research Council

C. B. Bazzoni (June, 1955)

### Representative on Council of American Association for the Advancement of Science

Roland F. Beers, Beers and Heroy, Troy, N. Y.

* SEG Members.

## MEMBERSHIP APPLICATIONS RECEIVED

Applications for Active membership have been received from the following candidates. This publication does not constitute an election but places the names before the membership at large, in accordance with Bylaws, Article III, Section 4. If any member has information bearing on the qualifications of these candidates he should send it to the President within thirty days.

ANDERSON, EDMUND HUGHES, *Seismologist-Party Chief*, Shell Oil Company, Box 193, New Orleans, La.

ANDERSON, RALPH GORDON, *Party Chief*, Continental Geophysical Company, 820 North Mueller, Bethany, Okla.

BABOIN, GUY EUGENE, *Vice President, Operations*, Schlumberger Overseas, S. A., 42, Rue Saint-Dominique, Paris, France

BATH, GORDON DANIEL, *Geophysicist*, U. S. Geological Survey, 4 Homewood Pl., Menlo Park, Calif.

COOK, LYNN RANDOLPH, JR., *District Geologist*, Richmond Exploration Co., Apartado 93, Maracaibo, Venezuela

CESANELLI, METELLO, *Supervisor*, YPF-Argentine Government Oil Fields, Apartado 1, Barrio Gral Mosconi-Comodoro Rivadavia, Argentina

COCHRANE, JOHN MACGREGOR, *Supervisor*, Jones-Shelburne, Inc., 1913 Huntington Ave. Oklahoma City, Okla.

EHLERT, GILBERT WESLEY, *Seismic Party Chief*, Magnolia Petroleum Company, Box 637, Cotulla, Tex.

EICHER, DONALD BOYD, c/o Egyptian American Oil Company, Box 50, Cairo, Egypt

ENGLISH, IVAN JAMES WHITNEY, *Party Chief*, Canadian Exploration Company, Ltd., 340—7th Ave. West, Calgary, Alta., Canada

FEDUKOWICZ, WACLAW, *Geophysicist*, Sherwin F. Kelly Company, 415 Jerome St., Brooklyn 7, N. Y.

FERGUSON, PAUL MARION, *Research Engineer*, Seismograph Service Corporation, 1703 N. College, Tulsa 10, Okla.

FERRÉ, MAURICE C., *Head Research Department*, Schlumberger Well Surveying Corp., Box 432, Ridgefield, Conn.

GILBERT, HOWARD JAMES, *Supervisor*, General Geophysical Company, 2802 Post Oak Road, Houston, Tex.

HALL, ORVILLE WOODROW, *Seismologist*, Marine Exploration Co., 2001 Brun Street, Houston 19, Tex.

HENDERSON, ROLAND GEORGE, *Mathematician*, U. S. Geological Survey, 1812 A Street, S. E., Washington 3, D. C.

INGALL, LINDSAY NEIL, *Geophysicist*, Canadian Gulf Oil Company, Peace River, Alberta, Canada

JAMISON, ROY BLAND

KILBACK, NORMAN ROBERT, *Party Chief*, Canadian Gulf Oil Company, Party 17, Clarsesholm, Alberta, Canada

KIMBELL, CHARLES LEWIS, *Electronic Engineer*, McCollum Laboratories, Inc., 728 E. 17th St., Houston, Tex.

KIRK, DAVID KELLER, *Geophysicist*, Gulf Oil Company, Box 968, Ardmore, Okla.

KROGER, WILBUR LEMOYN, *Seismologist*, Shell Oil Company, 226 Nelson Drive, Baton Rouge, La.

LEISURE, JOHN, JR., *Geophysical Reviewer*, Cities Service Oil Company, 1818 Crestview, Bartlesville, Okla.

MANDLEBAUM, HUGO, *Ass't Professor*, Wayne University, 4030 Richton, Detroit 4, Mich.

MATHIEU, JEAN LEON, *Directeur de l'Exploitation*, Societe De Prospection Electrique, 42, rue St-Dominique, Paris 7e, France

NOVOTNY, JEROME DOUGLAS, *Supervisor*, Stanolind Oil & Gas Company, Box 268, Lubbock, Tex.

PARRACK, ALVIN LANDIS, *Research Engineer*, The Texas Company, 601 Maryem, College Station, Tex.

RICHARDS, JOSEPH MCCLELLAND, *Senior Engineer*, Geophysical Measurements Corp., 804 Wright Building, Tulsa, Okla.

SEYDOUX, A. E. R., *President*, Societé de Prospection Electrique, 42 Rue Saint-Dominique, Paris 7e, France

SCOTT, EDWARD WILLIAM, *Chief Geologist, Williston Basin*, Union Oil Co. of Calif., 1125 Union Oil Building, 617 West 7th St., Los Angeles 17, Calif.

SWISTEK, JOHN, *Seismologist*, Sun Oil Company, 600 Barron Building, Calgary, Alta., Canada

VASTINE, THOMAS JUDSON, *Seismograph Interpreter*, Gulf Research Corporation, Drawer 2038, Pittsburgh 30, Pa.

### TRANSFER TO ACTIVE MEMBERSHIP

ARCENEAU, JULIUS EMMETT, *Party Chief*, Geophysical Service Inc., 5900 Lemmon Ave., Dallas 9, Tex.

BONE, ROBERT MARVIN, *Geophysicist*, The Ohio Oil Company, Box 2351, Casper, Wyo.

BROOKS, WILLIAM THOMAS, *Party Chief*, Western Geophysical Co. of America, Box 159, Casper, Wyo.

BURKHALTER, HOWARD LEE, *Party Chief*, General Geophysical Company, 2514 Gulf Building, Houston, Tex.

DANIEL, ROBERT EDWARD, *Geophysicist*, The California Standard Company, Medical Arts Building, Calgary, Alta., Canada

DARDEN, DAVID BRAXTON, *Party Chief*, Sohio Petroleum Co., Box 13176, Houston 19, Tex.

ERGIN, KAZIM, *Director of Geological Division*, M.T.A. Institute of Turkey, Enstitusu, Ankara, Turkey

HAMILL, ROBERT MAGEE, *Seismologist*, Broussard Exploration Co., 2015 S. Shepherd, Houston 19, Tex.

HAMMOND, DEAN HARLOW, *Party Chief*, The Texas Company, Box 299, Belfield, N. D.

HECK, HENRY WILLIAM, *Geophysicist*, Gulf Research & Development Company, Drawer 2038, Pittsburgh 30, Pa.

JENNEMANN, VINCENT FRANCIS, *Research Engineer*, Stanolind Oil & Gas Company, Box 591, Tulsa, Okla.

KING, WILLIAM SWEITZER, *Geologist*, The Texas Company, 142 Steckel Drive, Santa Paula, Calif.

LOMBARDI, LEONARD VOLK, *Geophysicist*, Gulf Oil Corporation, Drawer 1290, Fort Worth 1, Tex.

MARTIN, RICHARD GEORGE, *Party Chief*, Geophysical Consultants, Inc., Box. 566, Great Bend, Kan.

MATTHEWS, E. W., JR., *Jr. Geophysicist*, Sinclair Oil & Gas Co., 901 Fair Building, Fort Worth 2, Tex.

MORLEY, LAWRENCE W., *Chief, Geophysics Section*, Geological Survey of Canada, Box 44, Billings Bridge P. O., Ottawa, Ontario, Canada

REESE, JOHN RENOWDEN, *Geophysicist*, The California Company, 800 The California Company Building, New Orleans, La.

ROGERS, GEORGE REINER, *Geophysicist*, Bear Creek Mining Company, 516 Acoma St., Denver 4, Colo.

ROY, AMALENDU, *Ass't Geophysicist*, Government of India, Geological Survey of India, 27 Chowringhee Road, Calcutta 13, India

SANDER, GEORGE WOLFGANG, *Geophysicist*, Western Geophysical Co. of Canada, 828 4th Ave. West, Calgary, Alberta, Canada

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## REPORTS BY OFFICERS AND COMMITTEES

### REPORT OF THE SPECIAL COMMITTEE ON A CODE OF ETHICS

The Special Committee on a Code of Ethics, consisting of J. A. Brooks, Jr., Cecil H. Green and George E. Wagoner, after careful study recommends to the Executive Committee the following first draft of a Code of Ethics for the SEG:

The Constitution of the SEG, Article IV, Section 1 states that, "Membership of any class shall be contingent upon conformance with the established principles of professional ethics."

As an elaboration of these established principles of professional ethics the following Code of Ethics is enunciated. It shall be the duty of every geophysicist, in order to maintain the dignity of his chosen profession:

1. To carry on his professional work in a spirit of fidelity to clients and employers, fairness to employees and contractors, and devotion to high ideals of personal honor.

2. To treat as confidential his knowledge of the business affairs, geophysical or geological information, or technical processes of clients or employers when their interests require secrecy.

3. To inform a client or employer of any business connections, interests, or affiliations which might influence his judgment or impair the disinterested quality of his services.

4. To accept financial or other compensation for a particular service from one source only, except with the full knowledge and consent of all interested parties.

5. To refrain from associating himself with, or knowingly to allow the use of his name by, any enterprise of questionable character.

6. To advertise only in a manner consistent with the dignity of the profession, to refrain from using any improper or questionable methods of soliciting professional work, and to decline to pay or to accept compensation for work secured by such improper or questionable methods.

7. To refrain from using unfair means to win professional advancement, and to avoid injuring unfairly or maliciously, directly or indirectly, another geophysicist's professional reputation, business, or chances of employment.

8. To cooperate in building up the geophysical profession by the interchange of general information and experience with his fellow geophysicists and with students and also by contributions to the work of technical societies, schools of applied science, and the technical press.

9. To interest himself in the public welfare and to be ready to apply his special knowledge, skill, and training in the public behalf for the use and benefit of mankind.

The Special Committee recommends that any Code of Ethics be offered to the Society as only a definition of professional ethics for geophysicists. The Committee emphatically recommends that a Code of Ethics not be made a part of the Constitution or By-Laws of the Society. It also recommends that no detailed provision for enforcement of the Code be made.

The Special Committee will await the reaction of the Executive Committee to these recommendations and your instructions before proceeding with a final report for submission to the Annual Meeting.

J. A. BROOKS, JR.

July 6, 1954

for the Committee

## REPORT OF SEG COMMITTEE ON STANDARDIZATION OF MAGNETIC RECORDING OF SEISMIC SIGNALS

*Committee Personnel*

| | |
|---|---|
| R. R. Thompson | The Carter Oil Company |
| K. R. Beeman | Southwestern Industrial Electronics Company |
| R. F. Beers | Beers and Heroy |
| K. E. Burg | Geophysical Service Incorporated |
| G. M. Grosjean | Techno Instrument Company |
| J. E. Hawkins | Seismograph Service Corporation |
| K. M. Lawrence | Amerada Petroleum Company |
| B. D. Lee | The Texas Company |
| R. A. Peterson | United Geophysical Company |
| J. E. White | Magnolia Petroleum Company |

The SEG Committee on the Standardization of Magnetic Recording of Seismic Signals has been set up in response to the concern expressed (largely on the part of potential users of magnetic recording) over the wide variety of recording equipment now being offered to the industry or being announced as under development. This Committee has been asked by the Executive Committee of the SEG to study the problem and to make such recommendations as may seem to be desirable and beneficial to the industry. The first meeting of the Committee was held in Tulsa, Oklahoma, June 28, 1954.

In considering the standardization problem, the Committee recognizes a number of important factors. It is believed that magnetic recording represents a basically important advance in the recording of seismic data. The possible uses and applications of this new recording medium cover a wide range and are moreover in an early stage of development. It is important that no steps be taken which will hamper future progress in this most important field. At the same time there are areas where some degree of uniformity can be introduced with mutual benefit to all concerned.

At the present time some confusion exists regarding the meaning of the characteristics quoted by the manufacturer for the various types of equipment now available. For example, such quantities

as dynamic range, signal to noise, distortion, etc. are measured in different ways and specified differently by different manufacturers. It is the feeling of the Committee that agreement can now be reached on definitions and measurement procedures and that this step should be undertaken.

Another problem is pointed up by the concern over the difficulty of playing back records of different types which may be acquired by a user of magnetic recording. It is expected that some users, whether they employ contract crews or purchase equipment for use on their own crews, will want to play back the records in their own laboratories for evaluating certain uses. Also, future developments may make it desirable to rework the records at a future date. For these and other reasons, unlimited variations in recorder characteristics and dimensions may prove a handicap to the most effective use of magnetic recording.

It is recognized, on the other hand, that various types of recorders have advantages for various uses and these types, such as the disc, drum, and tape recorders now in use, are desirable in evaluating the ultimate potentialities of these uses. However, within a particular type it may be that certain features (for example, head spacing, recording speed, carrier frequency) could be limited to a few preferred values with no hampering effects.

One solution to the play-back problem may be the development of record translators which will accept records of various types and transcribe them into records of a particular, desired type. At least one manufacturer is already considering the development of such a translating device. In this connection, the limited standardization suggested above would simplify the translator development problem.

To implement the Committee's proposals, it was recommended that two subcommittees be set up: one to deal with the problem of definitions and measurement procedures, and the other to study engineering practices and to recommend from time to time equipment features which might be standardized.

Mr. William E. H. Doty has agreed to serve as chairman of the subcommittee on Definitions and Measurement Procedures, and it is expected that the work of this committee will get under way promptly. Further study is being given to the formation of a subcommittee on Engineering Practices.

Respectfully submitted,
R. R. THOMPSON, Chairman

## SEG POLICY ON PUBLICATION OF TECHNICAL PAPERS PRESENTED AT SOCIETY MEETINGS

The following regulations, approved by the SEG Executive Committee, supersede the Society's previous regulations on the above subject as published in the January, 1948 issue of GEOPHYSICS (Vol. XIII, p. 147):

1. When a paper is accepted for presentation at an annual or regional meeting of the Society, its author is ordinarily expected to submit, within a reasonable time, a manuscript of the paper for possible publication in GEOPHYSICS. Papers are accepted for oral presentation with the understanding that the Society is thereby given first claim to publication of the material in the paper. An exception is made in the case of papers previously published, or submitted for publication, elsewhere which are solicited for oral presentation at a meeting and approved for such presentation by the Program Chairman. If prior commitments or other special circumstances prevent an author from submitting to GEOPHYSICS the manuscript of a paper which he wishes to present at a Society meeting, he should inform the Program Chairman of these circumstances at the time he offers his paper for the meeting. Program chairmen are requested to inform the Editor of all papers on their programs which are ineligible or unavailable for publication in GEOPHYSICS.

2. The Business Manager may allow advance reproduction of titles and abstracts for any or all papers on the program of a regional or annual meeting.

3. Any request from a trade journal or similar publication for the manuscript of a paper presented orally, or scheduled for such presentation, at a Society meeting but not yet published, should be addressed to the Editor of GEOPHYSICS. If the author prefers publication in the trade journal to publication in GEOPHYSICS, the Editor may, at his discretion, release publication rights to the trade

journal. The annual Presidential Address and Review of Geophysical Activity will continue to be released for publication by trade journals at the time of the annual meeting and will be published in GEOPHYSICS subsequently. Under very special circumstances, other papers may be released by the Editor for outside publication in advance of their appearance in the Society's journal. In all instances, acknowledgment must be made to the Society and specific mention made of the SEG meeting where the paper was first presented.

If a paper presented at a Society meeting is submitted to GEOPHYSICS and is not accepted for publication, it becomes the property of the author, who may then submit it to any other publication he chooses.

4. Publication of popular versions in trade journals, newspapers, or magazines, of any paper presented orally at Society meetings will not affect the eligibility of such a paper for acceptance by GEOPHYSICS provided that the popular version is not so similar to the manuscript submitted for publication by the Society that the latter, in the Editor's opinion, makes no new contribution to the literature. Popular versions prepared by trade journal editorial staffs of papers presented at such meetings but not yet published in GEOPHYSICS should be approved before publication by the author and the Editor of GEOPHYSICS.

5. The Society's policy on republication of material already published in GEOPHYSICS is stated on the journal's mast-head page under the heading "Reprinting of Material from GEOPHYSICS."

## ANNOUNCEMENTS

### EIGHTH ANNUAL MIDWESTERN MEETING

As announced in the July issue of GEOPHYSICS, the Eighth Annual Midwestern Meeting of the Society of Exploration Geophysicists will be held November 18 and 19, 1954, at the Adolphus hotel in Dallas, Texas. Mr. R. C. Dunlap, who is General Chairman, has stated that registration will begin November 17 for more than 1,000 exploration scientists from Texas, Louisiana, Oklahoma and New Mexico. Meeting committees are headed by members of the Dallas Geophysical Society who are assisted by members of five other participating SEG local sections in Fort Worth, Midland, Shreveport, Oklahoma City, and Tulsa.

Committee chairmen appointed by Mr. Dunlap include: John T. Geer, Magnolia Petroleum Co., housing; Martin C. Kelsey, Rayflex Exploration Co., finance; L. L. Logue, Exploration Surveys, Inc., entertainment; John W. Wilson, Geophysical Service Inc., program publication; R. Maurice Tripp, Research, Inc., program; Howard L. Cobb, The Atlantic Refining Co., registration; Chester J. Donnally, Donnally Geophysical Co., arrangements; and John A. Lester, Magnolia Petroleum Co., publicity.

### PACIFIC COAST MEETING

The Pacific Coast Section of the SEG, AAPG and SEPM will hold its annual fall meeting at the Biltmore Hotel, Los Angeles, Thursday and Friday, November 11 and 12. The theme of this meeting is to be Marine Exploration and most of the papers are to be on this subject. The general chairman for the SEG for this meeting will be Harold C. Bemis of the Standard Oil Company of California; the program chairman will be Atch Curry of the Shell Oil Company; the arrangements chairman will be Andy Benston of the Standard Oil Company of California; the publicity chairman for the meeting is Dick Noble of the Humble Oil and Refining Company. SEG President Paul Lyons will speak at the luncheon meeting which will be held Friday, November 12.

### ANNOUNCEMENT
### of the
### DENVER MEETING
### SOCIETY OF EXPLORATION GEOPHYSICISTS

The first national meeting sponsored solely by the Society of Exploration Geophysicists will be held at the Shirley Savoy Hotel in Denver, Colorado on October 3, 4, 5, and 6, 1955. Technical papers

of interest to people in all branches of the exploration industry will be programmed and are herewith solicited. Authors will be requested to submit their manuscripts to their local representatives on the Program Committee.

Details of the convention as well as the committee rosters will be published in GEOPHYSICS at a later date.

Please note that the needs of the New York joint meeting have first priority but that an outstanding program must be presented at Denver at our first try "on our own."

ROBERT DYK
General Chairman

## CAREERS IN EXPLORATION GEOPHYSICS

The Society of Exploration Geophysicists has published a vocational guidance brochure for students in the 26,000 high schools of the United States and Canada. Petroleum companies, geophysical contractors, and universities have donated more than $13,000 for the booklet, "Careers in Exploration Geophysics," written by the Standing Committee on Public Relations under the chairmanship of R. C. Dunlap, Jr.

In a letter to the industry last January, Roy L. Lay, Past President of SEG, said "Geophysics needs to tell its story early. It needs to go to the high school and college student to present the possibilities of a career in geophysics. It needs to help the student at a time he is trying to make up his mind about a vocation—when he and his advisors are trying to find a proper channel for his interests and capabilities."

In response the Society has received pledges for all but $2,000 of the total needed to finance the original printing and distribution of one copy to each high school in time for fall enrollment. During July, 20,000 copies were delivered to companies supporting the project through purchases for use in their personnel departments, and more than 50,000 have been retained for answering inquiries from students. "Careers in Exploration Geophysics" serves a two-fold purpose. Originally designed to answer inquiries from high school students about geophysics as a vocation, the brochure offers brief explanations of the various exploration techniques and presents geophysical exploration as a challenging career. In addition the brochure is proving helpful to companies in the establishment of good public relations in the communities where their field crews are working. Several companies supply copies, bearing the company imprint, to party

R. C. Dunlap, Jr. (left), Chairman of the Standing Committee on Public Relations, and Reuben Erickson of Erickson Printing Company, Dallas, check one of the 500,000 impressions that comprise the 100,000 copies of "Careers in Exploration Geophysics."

chiefs for distribution to high school principals and vocational guidance directors. The brochure may be purchased for this purpose from the SEG Business Office, 624 South Cheyenne, Tulsa, Oklahoma, at the following prices:

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|---|---|
| 1 to 499 copies | 65 cents each |
| 500 to 999 copies | 60 cents each |
| 1,000 to 1,999 copies | 55 cents each |
| 2,000 or more copies | 50 cents each |

Proceeds from sales will be needed to finance distribution of the remaining 50,000 copies reserved for individual requests. Companies desiring to support this project are invited to send contributions to the Business Office.

R. C. Dunlap, Jr., Chairman of the Standing Committee on Public Relations, stands beside crates containing more than seven tons of paper on which 100,000 copies of "Careers in Exploration Geophysics" were printed.

## CONFERENCE ON RAW MATERIAL NEEDS OF U. S.

Dr. Arthur S. Flemming, Director of the Office of Defense Mobilization, will be a leading speaker at a conference on the raw material needs of the U. S., to be held in Dallas on November 15, 16 and 17. The conference will be sponsored by the Dallas Council on World Affairs, according to Glen G. Costin, Executive Director of the Council, and H. N. Mallon, DCWA president. Mr. Mallon is also president of Dresser Industries, Inc., Dallas.

Stockpiling for National Defense will be the subject of Dr. Flemming's address. Other topics scheduled for major addresses are Minerals in International Politics, Minerals in World Trade, Energy Sources for Industrial Growth, Mineral Requirements of an Expanding Economy, Known U. S. Resources, and Closing the Gap Through Increased Exploration, Beneficiation, Conservation and Substitution.

The conference will immediately precede the Dallas Midwestern meeting of the Society of Exploration Geophysicists, on November 18 and 19.

## NEW GEOPHYSICAL CURRICULUM

The Georgia Institute of Technology recently established an undergraduate curriculum leading to the Bachelor of Science in Physics, Geophysics Option. Requirements are substantially those suggested by the Geophysical Education Committee of the American Institute of Mining and Metallurgical Engineers in 1943, including the equivalent of an undergraduate major in physics with minors in both mathematics and geology, as well as appropriate course work in chemistry and engineering. Already there are 23 on departmental rolls, 5 of whom are graduating to contracting, mining, and oil companies. Although the curriculum was not approved formally until Christmas, 1953, the Institute has placed some 20 or 30 graduates in geophysical activities, including 3 holders of advanced degrees, within the last half decade.

## ADOPTION OF INTERNATIONAL NAUTICAL MILE

Beginning on July 1, 1954, the National Bureau of Standards will use the International Nautical Mile in lieu of the U. S. Nautical Mile. This decision, replacing the U. S. nautical mile of 1853.248 meters (6080.20 feet) by the International Nautical Mile of 1852 meters (6.076.10333 . . . feet), confirms an official agreement between the Secretary of Commerce and the Secretary of Defense to use the International Nautical Mile within their respective departments.

## 1955 OFFICER NOMINATIONS ANNOUNCED BY AAPG

EDWARD A. KOESTER, president of the American Association of Petroleum Geologists, announces that two New York City geologists, MARSHALL KAY, Columbia University, and G. M. KNEBEL, Standard Oil Company (N. J.), are candidates for the Association presidency during 1955–56. Other officer nominees revealed in the report of the A.A.P.G. nominating committee are: for vice-president, HORACE D. THOMAS, University of Wyoming, Laramie, and HENRY N. TOLER, consultant, Jackson, Mississippi; for secretary-treasurer, FRANK GOUIN, independent oil producer, Duncan Oklahoma, and W. A. WALDSCHMIDT, consultant, Midland, Texas; for editor, W. C. KRUMBEIN, Northwestern University, Evanston, Illinois, and GROVER E. MURRAY, Louisiana State University, Baton Rouge.

# PERSONAL ITEMS

JOHN H. HIDY became Senior Research Engineer with Seismograph Service Corp., Tulsa, Oklahoma in April, 1954.

KENNETH L. COOK, Head of the Department of Geophysics at the University of Utah, was recently appointed to the Executive Committee of the Mining, Geology, and Geophysics Division of the American Institute of Mining and Metallurgical Engineers.

The Atlantic Refining Company has announced the grant of a 1954–1955 scholarship in Geophysics at Colorado School of Mines to RICHARD O. BARNES, Normal, Illinois.

P. H. GARRISON has been promoted to Division Geophysical Supervisor for the Central division of Stanolind Oil and Gas Company.

CURTIS H. JOHNSON, a past president of SEG, has become Resident Director of Geophysical Service (Nederland) N.V., with headquarters in The Hague. He was previously Manager of The Marine Division of Geophysical Service Incorporated, with headquarters in Dallas.

H. W. STRALEY, III, Geologist and Geophysicist, Princeton, West Virginia, has just completed a gravity investigation in southern Georgia.

C. W. SANDERS has resigned from his position as Manager of Operations for Mendota Oil Company to open an office in the Snowden Building, 740 West Fifth Street, Fort Worth, Texas, to carry on his own operations and consulting practice.

J. D. NOVOTNY has been named Field Seismograph Supervisor for Stanolind Oil and Gas Company's Lubbock District where he will supervise seismic operations. Mr. Novotny replaces P. H.

GARRISON, who was transferred to Stanolind's Oklahoma City division office as Division Geophysical Supervisor.

HAMILTON MCKEE JOHNSON, who was formerly associated with the Schlumberger and Seismograph Service Corporation organizations in both the United States and Venezuela, has been awarded the Ph.D. degree in geology and geophysics by the University of Oklahoma. Dr. Johnson has assumed the position of geologist with the Texas Petroleum Company in their office in Caracas, Venezuela.

PETER C. BADGLEY has resigned as District Geologist for Husky Oil and Refining Ltd. in Alberta, to become Exploration Manager of West Maygill Gas and Oil Ltd., a newly organized petroleum producing company with producing properties in Alberta, Wyoming, and Kansas. Dr. Badgley will make his office in Calgary, Alberta.

JAMES R. WAIT, L. W. MORLEY, and L. S. COLLETT have been elected President, Secretary, and Treasurer, respectively, of the newly formed Ottawa Geophysical Discussion Club. This group, which has been meeting on an informal basis, is mainly interested in the fundamentals of earth physics rather than the applications. The members are composed of geophysicists from the Geological Survey of Canada, Dominion Observatory, Defence Research Board, and the National Research Council.

NOEL H. STEARN, Vice-President of W. C. McBride, Inc., St. Louis, Missouri, has retired to California where his address is 128 Goya Road, Menlo Park, California. Dr. Stearn joined W. C. McBride, Inc. in 1926 on a special geophysical research assignment in connection with the development of the Hotchkiss Superdip magnetometer. In 1930 he was made Chief Geologist, in 1940 Vice-President in charge of exploration, and in 1950 co-manager of the company. His connection with W. C. McBride, Inc. is being continued by a retainer for consultation privileges. Although he will also be available for consultation by others, he indicates that it will be at such an exorbitant fee that he can look forward confidently to a leisurely home life.

JOSEPH A. KORNFELD has resigned as District Editor of The Oil & Gas Journal to enter consulting geological and petroleum engineering work. He has opened offices at 301 Oil Capitol Building, Tulsa, Oklahoma.

NOBEL MUÑOZ, Geophysicist Engineer, formerly Geophysical Chief San George Gulf, Comodoro Rivadavia and Superior Technical Staff of the Geophysical Department of Yacimientos Petroliferos Fiscales, has resigned after twelve years service to open practice as a Consulting Geophysicist with offices at Paez 2246 and Lavalle 1783, 5° piso, Buenos Aires, Argentina.

E. O. VETTER has been appointed Assistant Vice-President, Administration, for Geophysical Service Inc., Dallas, Texas.

ROBERT E. SYKES, a Student member whose parents reside in Long Beach, California, received the Master of Science degree in geophysics at the New Mexico Institute of Mining and Technology, Socorro, New Mexico.

LEONARD B. LIPSON, formerly Senior Research Physicist at Magnolia's Field Research Laboratories, Dallas, has been appointed an Associate Professor of Petroleum Engineering at the University of Houston, starting September 1, 1954. Dr. Lipson plans to conduct research on core analyses and well logging.

W. JACQUE YOST has resigned his position as Technical Assistant to the Director of the Field Research Laboratories, Magnolia Petroleum Company, effective October 1, to accept a newly-created position as Director of Research for the Ohio Oil Company.

HERBERT HOOVER, JR. has been appointed Undersecretary of State by President Eisenhower. His appointment has been approved by Congress and he will soon take up his duties in Washington. Mr. Hoover has resigned his position as a director of Union Oil Company of California. At the meeting at which his resignation was accepted, the directors of the Union Oil Company announced the sale of the United Geophysical Company, formerly a subsidiary, to the United Geophysical Corporation, formed by the officers and area managers of the United organization.

LAWRENCE B. LUHRS, Computer for Geophysical Service Inc., has moved from Calgary, Alberta to Girvin, Sask., Canada.

ROBERT H. LOMMEN, formerly with Newmont Exploration Limited, Jerome, Arizona, is now with Shell Oil Company, 1008 West Sixth Street, Los Angeles 17, California.

EDGAR O. MCCUTCHEN, Western Geophysical Company, is now on Party No. 28, Box 922, Tyler, Texas.

E. J. MARTI, formerly Supervisor for United Geophysical Company, Inc., is now with Union Oil Company of California, 800 Prudential Building, Houston, Texas.

JACK A. RAMSDELL has moved from Raton, New Mexico, and is now with Hudson's Bay Oil & Gas, 534-A 8th Avenue West, Calgary, Alberta, Canada.

SGT. DAVID J. STOLWYK, formerly with the Engineer Test Unit, Ft. Belvoir, Virginia, is now in Hq Hq Co., Special Troops, USARAL, APO 949, c/o Postmaster, Seattle, Washington.

GENE C. SIGLE, Geophysical Section, Continental Oil Co., has moved from Jennings, Louisiana to Ponca City, Oklahoma.

JAMES E. WILSON, Division Geologist for Shell Oil Company, has transferred from Casper, Wyoming to 1845 Sherman Street, Denver 3, Colorado.

HARTMUT WINKLER, of Ownamin Limited, has transferred from Toronto to R.R. 3, West Bathurst, New Brunswick, Canada.

## SEG SAFETY COMMITTEE RECEIVES NSC AWARD

The SEG Standing Committee on Safety has been granted a National Safety Council Association Award for 1954 in recognition of the Committee's safety efforts.

The award was announced by Mr. A. M. Baltzer, Director of Small Business and Association Program, National Safety Council. Mr. Baltzer indicated that the Award was one of eleven made in 1954 with major emphasis upon the Associations' efforts rather than upon achievements.

Presentation of the Award will be made to the Chairman of the Committee on Safety, John F. Imle, by the Council's President, Ned H. Dearborn, at a luncheon on October 19 at the Morrison Hotel in Chicago as a part of the National Safety Congress which will be in session during that entire week.

The Safety Committee maintains Association membership in the National Safety Council, and, as a result, draws upon the Council's facilities in helping promote safety activity within the geophysical industry.

# SOCIETY OF EXPLORATION GEOPHYSICISTS
# CONSTITUTION AND BYLAWS

## CONSTITUTION

(As amended to August 26, 1948)


| | | | |
|---|---|---|---|
| Article I. | Name | Article X. | Meetings |
| Article II. | Object | Article XI. | Local Sections |
| Article III. | Membership | Article XII. | Districts |
| Article IV. | Code of Ethics | Article XIII. | Affiliated Socieites |
| Article V. | Election, et cetera, of Members | Article XIV. | Committees |
| Article VI. | Officers | Article XV. | Business Manager |
| Article VII. | Duties of Officers | Article XVI. | Review by Members |
| Article VIII. | Council | Article XVII. | Bylaws |
| Article IX. | Executive Committee | Article XVIII. | Amendments to the Constitution |


### Article I. Name

Section 1. The Society shall be called the "Society of Exploration Geophysicists."

### Article II. Object

Section 1. The objects of this Society shall be to promote the science of geophysics especially as it relates to exploration and research, to foster the common scientific interests of geophysicists, and to maintain a high professional standing among its members.

### Article III. Membership

Section 1. The membership of this Society shall consist of persons elected and qualified in accordance with the Constitution and Bylaws of this Society at the time of such election.

Section 2. The membership of this Society shall consist of Honorary Members, Active Members, Associate Members, and Student Members.

Section 3. To be eligible to election to Honorary Membership a person shall, in the unanimous opinion of the Standing Committee on Honors and Awards and the Council, have made a distinguished contribution to geophysics or a related field which warrants exceptional recognition.

Section 4. To be eligible to election to Active Membership an applicant must have been actively engaged in practicing or teaching geophysics or a related field for not less than eight years (up to four years as a student in a recognized college or university may be counted toward this total) of which at least three years must have involved work of a responsible nature calling for independent judgment and the application of geophysical or geological principles.

Section 5. To be eligible to election to Associate Membership, an applicant must be actively interested in geophysics.

Section 6. To be eligible to election to Student Membership an applicant must be a graduate or undergraduate student in good standing in residence at a recognized university or college.

Section 7. An Honorary Member or Active Member shall enjoy all privileges of the Society. He shall be eligible to hold any office, to vote on all matters submitted to the membership, to petition the Council or Executive Committee on any matter, to sponsor applicants for membership and to publish his affiliation with the Society.

Section 8. An Associate Member or Student Member shall be entitled to attend the meetings of the Society, to receive its Journal and to purchase its publications, on the same terms as an Active Member. He shall have none of the other privileges of membership and in publishing his affiliation with the Society shall clearly indicate his grade of membership.

### Article IV. Code of Ethics

Section 1. Membership of any class shall be contingent upon conformance with the established principles of professional ethics.

### Article V. Election, Resignation and Expulsion of Members

Section 1. The method of election to the various grades of membership shall be as set forth in the Bylaws.

Section 2. Any member in good standing may resign from the Society at any time as set forth in the Bylaws.

Section 3. Any member may for the good of the Society be suspended or expelled from the Society at any time as set forth in the Bylaws.

### Article VI. Officers

Section 1. The officers of the Society shall be a President, a Vice-President, a Secretary-Treasurer, and an Editor. Officers shall be elected in the manner prescribed in the Bylaws for a term of one year with the exception of the Editor, whose term shall be two years.

Section 2. Election of officers shall be by secret mail ballot. On the ballot shall be printed the nominees for each office arranged in alphabetical order.

Section 3. The Standing Committee on Nominations shall nominate, in the manner prescribed in the Bylaws, two candidates for each office to be filled. Further nominations may be made by petition as set forth in the Bylaws.

Section 4. The officers shall assume the duties of their respective offices immediately after the close of the Annual Meeting following their election.

Section 5. No officer shall be eligible for election to the same office for two consecutive terms.

Section 6. In case of a vacancy in any office, other than the President's, the Executive Committee shall select a successor to serve until the close of the Annual Meeting following this appointment.

### Article VII. Duties of Officers

Section 1. The President shall be the presiding officer at all the meetings of the Society, shall take cognizance of the acts of the Society and of its officers, shall appoint such standing committees and special committees as are required for the purposes of the Society, and shall delegate members to represent the Society. He may, at his option, serve on, and may be chairman of, any committee. He shall prepare an address to be given before the members of the Society at the Annual Meeting.

Section 2. The Vice-President shall assume the office of President in case of a vacancy from any cause in that office and shall assume the duties of President in case of the absence or disability of the latter. He shall also be responsible for all national meetings of the Society.

Section 3. The Secretary-Treasurer shall assume the duties of the President in case of the absence of both the President and Vice-President. He shall have charge of the financial affairs of the Society and shall annually submit reports as Secretary-Treasurer covering the fiscal year, which he shall arrange to have published in the next regular issue of the Journal of the Society. Under the direction of the Council, he shall arrange for the receipt and disbursal of all Society funds. He shall cause an audit to be prepared annually by a public accountant at the expense of the Society. He shall give a bond, and shall cause to be bonded, all employees to whom authority may be delegated to handle Society funds. The amount of such bonds shall be set by the Council and the expense shall be borne by the Society.

Section 4. The Editor shall be in charge of the editorial business, shall submit an annual report of such business, shall have authority to solicit papers and material for the regular Society publication and for special publications, and may accept or reject material offered for publication. He may appoint associate, regional, and special editors.

### Article VIII. Council

Section 1. The Council of the Society shall consist of the officers, the Past President, the Prior Past President, and all elected District Representatives.

Section 2. The Council shall be the governing body of the Society and subject to the provisions of the Constitution and Bylaws shall have full control and management of the affairs and funds of the Society.

Section 3. A joint meeting of the outgoing and incoming Councils shall be held at the call and under the chairmanship of the newly elected President during or within seven days after the Annual Meeting of the Society. At this joint meeting the Councils shall hear reports from all officers and committees and review the activities of the Society for the past year. With the advice of the outgoing Council, the incoming Council shall conduct any necessary business and issue instructions or recommendations to any officer or committee, subject to the provisions of the Constitution and Bylaws. All committee chairmen shall attend this meeting, but, as chairmen, shall have no vote.

Section 4. At the call of the President or a majority of the Council members, and after written notice to all Council members, the Council may meet at any time.

Section 5. A quorum at any meeting of the Council shall consist of six Council members.

Section 6. Unless otherwise provided by the Constitution, all actions by the Council shall require a majority vote of the members present.

### Article IX. Executive Committee

Section 1. The Executive Committee shall consist of the President, the Vice-President, the Secretary-Treasurer, the Editor, and the Past President.

Section 2. When the Council is not in session the Executive Committee shall have full authority, subject only to prior instructions by the Council, to exercise all powers of the Council.

Section 3. All actions of the Executive Committee shall require a majority vote of all members of the Committee

Section 4. The Executive Committee may vote on any matter either by mail or in person.

### Article X. Meetings

Section 1. The Society shall hold at least one meeting of the members each year, this meeting to be known as the Annual Meeting. One session of this meeting shall be a Business Meeting, at which reports of the officers and committees shall be read and the result of the mail ballot for officers announced.

Section 2. The Annual Meeting shall be held at a time and place designated by the Executive Committee.

Section 3. Additional meetings of the Society may be called by the Executive Committee.

### Article XI. Local Sections

Section 1. Local sections, consisting of members of the Society and other persons engaged in geophysics or a related field residing within an appropriate distance of a central point, may be organized as provided in the Bylaws.

Section 2. Each local section shall assist in carrying out the objectives of the Society within the territory assigned to the section by the Council.

Section 3. Each local section shall have one District Representative if among its members there are less than seventy-five Honorary Members and Active Members of the Society in good standing, two District Representatives if more than seventy-five and less than one hundred fifty, or three District Prepresentatives if more than one hundred fifty.

Section 4. The District representatives shall be elected from among the Honorary Members and Active Members of the Society in good standing for terms stated and in the manner prescribed in the Bylaws and shall not be eligible for two consecutive terms.

### Article XII. Districts

Section 1. The Council shall divide the area of the continental United States, not assigned to local sections, into not more than seven districts. Council may designate districts outside the area of the continental United States.

Section 2. Each district shall have for each seventy-five Active Members of the Society, who are not members of a local section, one District Representative, who shall be appointed by the President for a term of one year expiring at the close of the Annual Meeting.

### Article XIII. Affiliated Societies

Section 1. The Council may arrange for affiliation of the Society with any duly organized groups or societies.

Section 2. The terms of affiliation must provide that the Society shall have the right to dissolve such affiliation at any time, subject only to the payment of any sums it may legally owe the affiliated group or society.

### Article XIV. Committees

Section 1. In addition to the Executive Committee, there shall be appointed standing committees to further the purposes of the Society.

Section 2. The duties of the standing committees and the method of their appointment shall be in accordance with the Bylaws.

Section 3. The President may at any time appoint special committees for such purposes as he may deem fit.

Section 4. The terms of all special committees shall expire at the close of the Annual Meeting following their appointment.

### Article XV. Business Manager

Section 1. The Council may employ a business manager for the Society and pay him such salary and other compensations from the Society's funds as they deem advisable.

Section 2. The business manager shall provide a bond appropriate in amount, the cost to be borne by the Society.

Section 3. The business manager shall, under the supervision of the Secretary-Treasurer, perform such duties as the Council may assign him.

Section 4. The Council may discharge the business manager at any time.

### Article XVI. Review by Members

Section 1. All acts of the officers, Council, and committees of the Society shall be subject to review by the members.

Section 2. Proposals to change any decision, policy, or procedure of any officer, the Council, or any committee shall be submitted in writing to the President and signed by at least twenty-five Honorary and Active Mimbers in good standing.

Section 3. Upon receipt of such a petition with a sufficient number of valid signatures, the President shall advise the Council and the officer or committee involved.

Section 4. Should the officer or committee involved be unwilling to comply with the petition, it, together with a discussion by the proposer and the officer or committee involved, shall be published in the next issue of the Society's journal.

Section 5. Within thirty days after publication in the journal, the petition shall be submitted to the membership by mail ballot by the President. A majority of the ballots returned within thirty days after being mailed by the President shall be decisive. Should the vote favor the petition, it shall be complied with, within the limitations imposed by the Constitution and Bylaws, as promptly as practicable.

### Article XVII. Bylaws

Section 1. The Council shall make such Bylaws not in conflict with the Constitution, as it may deem necessary for the proper government of the Society. The Council may amend the Bylaws at the annual joint meeting by an affirmative vote of two-thirds of the members of the incoming Council present. All proposed amendments must, however, be published in the Society's journal before being submitted to the Council.

### Article XVIII. Amendments to the Constitution

Section 1. Amendments to this Constitution may be proposed by any ten members of the Society, by any officer of the Society, or by a Constitutional Committee appointed by the President.

Section 2. Any proposed amendment shall be submitted to the President in time for publication in the Society's journal prior to the Annual Meeting.

Section 3. At the annual joint meeting of the Council, all proposed amendments received since the previous Annual Meeting, shall be considered. Those receiving approval from a majority of the members of the incoming Council present shall be submitted by mail ballot, arranged by the Secretary-Treasurer, to the entire membership of the Society within sixty days. If a majority of the ballots returned within sixty days of their mailing favor the proposed amendment, it shall become effective at the expiration of this sixty days. All amendments shall be reported in the Society's journal.

## BYLAWS

(As amended to July 16, 1954)

Article I. Publications
Article II. Election of Honorary Members
Article III. Election of Active, Associate and Student Members
Article IV. Dues
Article V. Resignation of Members
Article VI. Expulsion of Members
Article VII. Election of Officers
Article VIII. Local Sections
Article IX. Finances of Local Sections
Article X. Standing Committees

### Article I. Publications

Section 1. The Society shall publish a journal entitled Geophysics

Section 2. The journal shall be published at intervals designated by the Executive Committee.

Section 3. All reports to the Society by its officers and committees shall be published in the journal. All members of the Society shall be presumed to have due notice of all Society matters published in the journal. Each issue shall contain a membership list of all standing and special Committees.

Section 4. Original papers, reviews, abstracts, notes or letters containing information deemed by the Editor to be of interest to the members of the Society shall be published in the journal. The Editor shall be the sole judge of whether such material is to be published.

Section 5. The subscription rate of the journal shall be $9.00 ($9.50 foreign) per year to nonmembers and $4.50 per year to members. The first $4.50 of the annual dues of each dues paying member shall be set aside for the payment of his subscription to the journal. Members of affiliated societies shall be entitled to receive the journal upon payment of a fee equivalent to the dues charged to an associate member.

Section 6. The Council may at its annual joint meeting authorize the printing of special publications to be financed and distributed in a manner approved by the Council.

### Article II. Election of Honorary Members

Section 1. The Standing Committee on Honors and Awards may submit to the President ninety days before the Annual Meeting the names of any person or persons they deem eligible to election as an Honorary Member. Their report shall explain the basis of their recommendation.

SECTION 2. The President shall submit copies of any such reports to all members of the Council not less than sixty days before the Annual Meeting.

SECTION 3. The Council members shall consider all such reports and vote by mail thirty days before the Annual Meeting. Unanimous action by those voting shall be required to elect any person as an Honorary Member.

### ARTICLE III. ELECTION TO ACTIVE, ASSOCIATE AND STUDENT MEMBERSHIP

SECTION 1. An applicant for election to Active, Associate or Student Membership shall submit to the business manager of the Society an application setting forth in detail his education and experience. The application shall list the names and present addresses of persons who can verify the statements given therein. It shall list not less than three Active Members or Honorary Members of the Society, in good standing, who are personally acquainted with the training or experience of the applicant. This application shall be open to inspection at any time.

SECTION 2. The Executive Committee may waive the requirement of references from members of the Society for geographical or other reasons, if the applicant is otherwise eligible and furnishes other satisfactory references.

SECTION 3. The business manager shall write to all references for verification of the applicant's statements. All replies from references shall be considered confidential and shall not be disclosed except to the Executive Committee, without the references' prior written consent.

SECTION 4. The name of each applicant for Active membership shall be published in the next regular issue of the Society's Journal for approval by the membership at large. If no objection is received within thirty days after this publication, the applicant shall be deemed approved by the membership at large.

SECTION 5. An applicant for Active or Associate membership must be approved by a majority of the Executive Committee. An applicant for Student membership must be approved by the Secretary-Treasurer.

SECTION 6. When an applicant has been approved, he shall be notified in writing by the Business Manager. If he fails to make payment of full annual dues within four months after such notification, the Executive Committee may rescind his election. His membership shall date from the first day of the calendar year in which he makes his initial payment of dues and he shall receive the regular Society publications for that year.

SECTION 7. An Associate or Student Member may seek transfer to Active Membership by supplying added information to show that he has become eligible to election to Active Membership. The transfer shall be handled in the same manner as election to Active Membership. The Standing Committee on Membership may of its own initiative secure the necessary added information and submit it to the Executive Committee.

### ARTICLE IV. DUES

SECTION 1. Honorary members shall not be required to pay dues and shall receive the journal and other publications without charge.

SECTION 2. The annual dues of an Active or Associate Member of the Society shall be seven dollars and fifty cents ($7.50), which includes the cost of one subscription to the Society's journal.

SECTION 3. The annual dues of a Student Member of the Society shall be four dollars and fifty cents ($4.50), which includes the cost of one subscription to the Society's journal.

SECTION 4. Annual dues shall be payable in advance on January 1 of the calendar year. A bill shall be mailed to each Active, Associate or Student Member before that date, stating the amount of annual dues and the penalty for default. The Society's journal shall be withheld from members pending payment of dues, and Active Members failing to pay by ten days prior to the Annual Meeting shall have their votes in the annual mail ballot disqualified. Members in arrears shall lose all privileges of membership until such arrears are met.

### Article V. Resignation of Members

Section 1. Any member of the Society may resign at any time. Such resignation shall be submitted in writing to the Council.

Section 2. Any member who resigns under the provisions of Section 1 of this Article ceases to have any rights in the Society and ceases to incur further indebtedness to the Society.

Section 3. Any person who has ceased to be a member under Section 1 of this Article may be reinstated by unanimous vote of the Executive Committee subject to the payment of any outstanding dues and obligations which were incurred prior to the date when he ceased to be a member of the Society.

### Article VI. Expulsion of Members

Section 1. Any member who fails to pay his dues by the last day of the calendar year shall be automatically suspended from membership on that day. While he is suspended, he shall have no rights in the Society and shall not be charged any dues.

Section 2. A member who has been suspended more than one year shall be dropped from the Society by the Executive Committee.

Section 3. A suspended member will automatically be reinstated by payment of outstanding dues and obligations and the dues for the current calendar year.

Section 4. A member who has been dropped under the provisions of Section 2 of this Article may be reinstated by a majority vote of the Executive Committee subject to the payment of outstanding dues and obligations and the dues for the current calendar year.

Section 5. Any member who, after being granted a hearing by the Executive Committee, shall be found guilty of a violation of the established principles of professional ethics, or shall be found guilty of having made a false or misleading statement in his application for membership in the Society, shall be asked to resign from the Society by unanimous vote of the Executive Committee. The decision of the Executive Committee in all matters pertaining to the interpretation and execution of the provisions of this section shall be final.

### Article VII. Election of Officers

Section 1. The Standing Committee on Nominations shall consist of the President, the Past President, and the Prior Past President.

Section 2. The Standing Committee on Nominations shall nominate two or more candidates for each office to be filled. They must secure the consent of all candidates nominated.

Section 3. The Standing Committee on Nominations must submit their ticket to the President in time for publication in the April issue of the Society's journal.

Section 4. Prior to June 1, nominations in writing, signed by at least twenty Honorary Members or Active Members in good standing and accompanied by the written consent of the candidate, may be submitted to the President.

Section 5. Between June 1 and June 15, the Business Manager will prepare and mail to each member, eligible to vote, a ballot listing all candidates properly nominated for each office. With each ballot, the business manager shall send an official envelope having the member's name on the back.

Section 6. The Standing Committee on Nominations shall appoint a committee of tellers to count the ballots.

Section 7. Each member voting may cast one vote for each officer and shall return his ballot to the business manager in the official envelope carrying on the outside the written signature of the member submitting the ballot. Only ballots so prepared by members in good standing, and received by the business manager at his officially recognized address not later than July 31 shall be valid.

Section 8. The business manager shall indicate which ballots are valid, and shall deliver all ballots unopened to the tellers after August 1. The candidate receiving the greatest number of valid votes cast for an office shall be declared elected to that office. In case of a tie, the Standing Committee on Nominations shall decide by a secret vote which of the candidates shall be elected. Results of the

mail ballot shall be communicated to all candidates by the nominating committee on or before August 15.

### Article VIII. Local Sections

Section 1. Upon petition of twenty members in good standing residing within an appropriate distance of a central point, the Council may authorize the formation of a Local Section and assign a specific territory to the Local Section. The Council may decline to authorize the formation of a Local Section when in its judgment such an organization would not be compatible with the interests of the Society.

Section 2. In the organizing meeting of the section, all members of the Society residing in the territory assigned by the Council to the section shall be eligible to vote.

Section 3. The section shall be known as "The (name of place) Section of the Society of Exploration Geophysicists."

Section 4. The principal work of a section shall be the holding of regular meetings for the presentation and discussion of papers of interest to its members.

Section 5. The section shall adopt bylaws which must be approved by the Council of the Society and shall be consistent with the Constitution and Bylaws of the Society.

Section 6. The election of District Representatives by the Local Sections shall be by secret ballot. The term of office of a District Representative shall be two years; however, if the section is entitled to more than one representative, one of the representatives elected at the establishment of the section or added as the result of subsequent growth of the Section, shall be elected for a one year term if this is necessary to prevent the terms of all District Representatives from expiring simultaneously.

Section 7. District Representatives shall be elected at least three weeks prior to the Annual Meeting of the Society and shall take office at the close of the Annual Meeting.

Section 8. The Secretary of the Local Section shall submit to the Secretary-Treasurer of the Society a report of each meeting of the Local Section or its governing board within two weeks after the meeting. He shall submit to the Secretary-Treasurer of the Society the names of all officers and committee members within two weeks after their election or appointment.

Section 9. Any Local Section which for two consecutive years has among its membership fewer than twenty members in good standing of the Society shall automatically be dissolved by the Council at its annual joint meeting. The Council may at any time dissolve any Local Section for reasons it deems good and sufficient.

### Article IX. Finances of Local Sections

Section 1. The Society may, at the discretion of the Council, pay any portion of the necessary operating expenses of a Local Section up to the sum of the following amounts: (a) $100 per year; (b) $50 per meeting up to four meetings per year; (c) $0.50 per member of the Society.

Section 2. The Treasurer of the Local Section shall forward, from time to time, his application for such portions of the sum provided in Section 1 as may be needed to the Secretary-Treasurer of the Society, who will arrange for the issuance of a check for the requested amount to the Treasurer of the Local Section.

Section 3. Prior to the Annual Meeting, the Treasurer of each Local Section shall transmit to the Secretary-Treasurer of the Society, for approval by the Council, an itemized statement of the expenditure of the funds received from the Society during the preceding calendar year.

Section 4. Allocations to a Local Section for the year in which it is established shall be in proportion to the fraction of the calendar year remaining.

Section 5. The Local Section may levy dues or raise funds in any other manner, subject to the approval of the Council. Payment of local dues shall, however, not be a prerequisite to participation in any activity financed wholly or in part with funds received from the Society.

## Article X. Standing Committees

Section 1. The Society shall have the following standing committees: (a) Standing Committee on Nominations; (b) Standing Committee on Membership; (c) Standing Committee on Honors and Awards; (d) Standing Committee on Publications; (e) one or more General Committees for the Annual Meetings; (f) Standing Committee on Education; (g) Standing Committee on Student Membership; (h) Standing Committee on Distinguished Lectures; (i) Standing Committee on Radio Facilities; (j) Standing Committee on Reviews; (k) Standing Committee on Public Relations; (l) Standing Committee on Publicity; (m) Standing Committee on Geophysical Activity; and (n) Standing Committee on Safety.

Section 2. Each standing committee shall have a chairman, appointed by the President unless otherwise specified in these Bylaws. The chairman shall submit a report to the President of the Society at such intervals as the chairman may deem advisable but at least quarterly. He shall submit to the Council at its annual joint meeting a report covering the activities of the committee since the previous Annual Meeting.

Section 3. The Standing Committee on Nominations shall consist of the President who shall be chairman, the Past President, and Prior Past President. Its duties shall be to nominate candidates for officers, appoint tellers to count the ballots and to declare the election of the officers as prescribed in Article VII of these Bylaws.

Section 4. The Standing Committee on Membership shall consist of three Active or Honorary Members appointed for a period of one year by the President immediately following the Annual Meeting. One of the members appointed shall have been a member the preceding year. The Committee shall actively solicit applications for membership from those qualified. It shall work closely with the membership committees of the Local Sections.

Section 5. The Standing Committee on Honors and Awards shall consist of five Active or Honorary Members, none of whom shall have been members of the Society less than five years. The senior member of the committee shall retire after the Annual Meeting. Vacancies shall be filled by the President. The Committee shall recommend candidates for election to Honorary Membership to the Council. The Committee shall recommend to the Council the establishment of honors and awards and shall recommend candidates for all established honors and awards of the Society to the Council.

Section 6. The Standing Committee on Publications shall consist of five Active or Honorary Members who shall serve a two year term concurrent with the Editor and who shall be appointed by the Editor. The committee shall have the duty of advising and assisting the Editor. The Editor shall appoint the chairman of this committee.

Section 7. The General Committee for the Annual Meeting to be held in a given year shall consist of a General Chairman and such additional persons as he may deem desirable. The General Chairman shall be appointed by the President with the concurrence of the Vice-President one or more years in advance of the Annual Meeting for which he is responsible and shall serve until the completion of all business related to the Annual Meeting. The other members of the General Committee, the Chairmen and members of any Committees to handle specific phases of the Annual Meeting shall be appointed by the General Chairman. The General Committee for the Annual Meeting shall have the duty of arranging and holding the Annual Meeting at a time and place designated by the Executive Committee.

Section 8. The Standing Committee on Education shall consist of five persons appointed for one year by the President. The chairman shall be an Active or Honorary Member. The committee shall promote effective geophysical education.

Section 9. The Standing Committee on Student Membership shall consist of five persons appointed for one year by the President. The chairman shall be an Active or Honorary Member. The committee shall encourage the interest of students in geophysics and the Society.

Section 10. The Standing Committee on Distinguished Lectures shall consist of six persons appointed for three years by the President. The two senior members of the committee shall retire after

the Annual Meeting. The chairman of the committee shall be appointed for one year by the President, and shall be an Active or Honorary Member. The committee shall obtain distinguished lecturers in geophysics and plan and supervise tours by these lecturers to the Local Sections of the Society and other participating organizations.

SECTION 11. The Standing Committee on Radio Facilities shall consist of from 5 to 15 Active or Honorary Members appointed for one year by the President. The committee shall, upon request from its chairman, determine the opinions of the members of the geophysical industry concerning matters pertaining to the use of radio in geophysics.

SECTION 12. The Standing Committee on Reviews shall consist of from 5 to 10 members who need not be Active Members of the Society. The members and the chairman shall serve a two year term concurrent with the Editor and shall be appointed by the Editor. The committee shall prepare reviews of current geophysical literature for publication in GEOPHYSICS.

SECTION 13. The Standing Committee on Public Relations shall consist of a chairman, appointed for one year by the President, and such additional members, appointed for one year by the chairman, as he may deem desirable. The committee shall advise the officers and Council of the Society concerning matters pertaining to public relations, shall recommend public relations policy, and shall carry out projects to promote good public relations.

SECTION 14. The Standing Committee on Publicity shall consist of a chairman, appointed for one year by the President, and such additional members, appointed for one year by the chairman, as he may deem desirable. The committee shall prepare and arrange for the distribution of suitable publicity material for the press, radio, and other appropriate media.

SECTION 15. The Standing Committee on Geophysical Activity shall consist of four or more Active or Honorary Members of the Society appointed for a term of one year by the President. The committee shall conduct an annual survey of geophysical activities throughout the world. This report shall be presented before the Society at its Annual Meeting and published in the January issue of GEOPHYSICS. It may be made available for publication in leading trade journals for release at the time of the annual meeting.

SECTION 16. The Standing Committee on Safety shall consist of a chairman, appointed for one year by the President, and such additional members, appointed for one year by the chairman, as he may deem desirable. The committee shall recommend safety policy and shall carry out projects to promote safety in geophysical operations.

# INDEX TO GEOPHYSICS, VOLUME XIX


| | Vol. | No. | Page |
|---|---|---|---|
| Agocs, W. B., E. Bangs, and J. C. Rollins. Airborne magnetometer profile from Portland, Oregon to Albuquerque, New Mexico | XIX | 2 | 270 |
| Airborne magnetic gradiometer, The Gulf. W. E. Wickerham | XIX | 1 | 116 |
| Airborne magnetometer profile from Portland, Oregon to Albuquerque, New Mexico. W. B. Agocs, E. Bangs, and J. C. Rollins | XIX | 2 | 270 |
| Annual survey of geophysical education, 1953–1954 | XIX | 3 | 549 |
| Anomalies near Parry Sound, Ontario, The correlation between pre-Cambrian rock densities and Bouguer gravity. C. H. G. Oldham | XIX | 1 | 76 |
| Associate Editors of GEOPHYSICS, Introducing the | XIX | 1 | 154 |
| Bangs, E., see W. B. Agocs, et al. | XIX | 2 | 270 |
| Barnes, Virgil E., see Frederick Romberg | XIX | 3 | 438 |
| Birch, Francis. The present state of geothermal investigations | XIX | 4 | 645 |
| Blum, Harold A., see Harold D. Smith | XIX | 2 | 310 |
| Bouguer gravity anomalies near Parry Sound, Ontario, The correlation between pre-Cambrian rock densities and. C. H. G. Oldham | XIX | 1 | 76 |
| Break-point method, Effects of weathering on refraction depths calculated on a time-intercept method and N. N. Zirbel | XIX | 4 | 716 |
| Buckner, Guy O. Sub-surface electrical measurements about two plane interfaces | XIX | 2 | 297 |
| Case history: Dawn No. 156 Pool, Ontario, Gravity. Richard A. Pohly | XIX | 1 | 95 |
| Case history of Wild Goose Gas Field, Butte County, California. Wallace L. Matjasic | XIX | 3 | 509 |
| Cline, Paul James, Memorial. | XIX | 2 | 344 |
| Cook, Kenneth L. and Robert G. Van Nostrand. Interpretation of resistivity data over filled sinks | XIX | 4 | 761 |
| Correlation between pre-Cambrian rock densities and Bouguer gravity anomalies near Parry Sound, Ontario, The. C. H. G. Oldham | XIX | 1 | 76 |
| Cross-correlation filtering. Hal J. Jones and John Morrison | XIX | 4 | 660 |
| Dawn No. 156 Pool, Ontario, Gravity case history. Richard A. Pohly | XIX | 1 | 95 |
| Delaware Basin, Surface and near-surface waves in the. M. B. Dobrin, P. L. Lawrence, and Raymond Sengbush | XIX | 4 | 695 |
| Density plotting by digital computers, Least squares polynomial fitting to gravitational data and. Stephen M. Simpson, Jr. | XIX | 2 | 255 |
| Determination of dips and depths of geological layers by the seismic refraction method. Lindonor Mota | XIX | 2 | 242 |
| Devices for the construction of refracted rays. Raoul Vajk | XIX | 2 | 237 |
| Digital computers, Least squares polynomial fitting to gravitational data and density plotting by. Stephen M. Simpson, Jr. | XIX | 2 | 255 |
| Dix, C. Hewitt. The Method of Cagniard in seismic pulse problems | XIX | 4 | 722 |
| Dobrin, Milton B. Style guide for GEOPHYSICS | XIX | 1 | 141 |
| ———, P. L. Lawrence, and Raymond Sengbush. Surface and near-surface waves in the Delaware Basin | XIX | 4 | 695 |
| Dobyns, D. Ray and W. B. Roper. Geophysical history of Mamou Field, Evangeline Parish, Louisiana | XIX | 3 | 490 |
| Donn, William L., Maurice Ewing, and Frank Press. Performance of resonant seismometers | XIX | 4 | 802 |
| Education, 1953–54, Annual survey of geophysical | XIX | 3 | 549 |
| Effects of weathering on refraction depths calculated on a time-intercept method and break-point method. N. N. Zirbel. | XIX | 4 | 716 |
| Eisler, J. D., see J. F. Evans, et al. | XIX | 2 | 200 |
| Electrical measurements about two plane interfaces, Sub-surface. Guy O. Buckner. | XIX | 2 | 297 |
| Electromagnetic reflection method, A field evaluation of the Albert Orsinger and Robert Van Nostrand | XIX | 3 | 478 |
| Evans, J. F., C. F. Hadley, J. D. Eisler, and D. Silverman. Three-dimensional seismic wave model with both electrical and visual observation of waves | XIX | 2 | 200 |
| Ewing, Maurice, see William L. Donn, Jack Oliver, and Frank Press | | | |
| Exploration history (prior to the Cotton Valley discovery) of the Ruston Field, Lincoln Parish, Louisiana. J. Ryan Walker | XIX | 1 | 124 |

Faust, Lawrence Y. Some values available to students . . . . . XIX 2 337
Filtering associated with selective sampling of geophysical data. C. A. Swartz and V. M. Sokoloff . . . . . XIX 3 402
Filtering, Cross-correlation. Hal J. Jones and John Morrison . . . . . XIX 4 660

Geological and geophysical study of Pilot Knob (South), Travis County, Texas, A. Frederick Rombert and Virgil E. Barnes . . . . . XIX 3 438
Geometrical properties of residual maps, Some. Charles A. Swartz . . . . . XIX 1 46
Geophysical activity in 1953. Sigmund Hammer . . . . . XIX 3 517
Geophysical education, Annual survey of . . . . . XIX 3 549
Geophysical history of the Good Field, Borden County, Texas. Holland C. McCarver . . . . . XIX 4 791
Geophysical history of Mamou Field, Evangeline Parish, Louisiana. D. Ray Dobyns and W. B. Roper . . . . . XIX 3 490
Geophysical study of Pilot Knob (South), Travis County, Texas, A geological and. Frederick Romberg and Virgil E. Barnes . . . . . XIX 3 438
Geophysicist in industry, The. Roy L. Lay . . . . . XIX 3 383
Geothermal investigations, The present state of. Francis Birch . . . . . XIX 4 645
Good Field, Borden County, Texas, Geophysical history of the. Holland C. McCarver . . . . . XIX 4 791
Grant, Fraser S. A theory for the regional correction of potential field data . . . XIX 1 23
Gravitational data and density plotting by digital computers, Least squares polynomial fitting to. Stephen M. Simpson, Jr. . . . . XIX 2 255
Gravity anomalies near Parry Sound, Ontario, The correlation between pre-Cambrian rock densities and Bouguer. C. H. G. Oldham . . . . . XIX 1 76
Gravity case history: Dawn No. 156 Pool, Ontario, Richard A. Pohly . . . . XIX 1 95
Gravity maxima corresponding with sedimentary basins. Rodolfo Martin . . . XIX 1 89
Gravity, A note on downward continuation of. César A. Trejo . . . . . XIX 1 71
Gulf airborne magnetic gradiometer, The. W. E. Wickerham . . . . . XIX 1 116

Hadley, C. F., see J. F. Evans, et al. . . . . XIX 2 200
Hammer, Sigmund. Geophysical activity in 1953 . . . . . XIX 3 517
Hostetter, William Neal, Memorial . . . . . XIX 1 172

Interpretation of resistivity data over filled sinks. Kenneth L. Cook and Robert G. Van Nostrand. . . . . XIX 4 761
Introducing the Associate Editors of GEOPHYSICS. . . . . XIX 1 154

Jones, Jal J. and John Morrison. Cross-correlation filtering . . . . . XIX 4 660

Lawrence, P. L., see M. B. Dobrin, et al. . . . . XIX 4 695
Lay, Roy L. The geophysicist in industry . . . . . XIX 3 383
——— A message from the President . . . . . XIX 1 139
——— Our expanding horizons . . . . . XIX 2 191
Least squares polynomial fitting to gravitational data and density plotting by digital computers. Stephen M. Simpson, Jr. . . . . XIX 2 255
Logn, Ö. Mapping nearly vertical discontinuities by earth resistivities . . . . XIX 4 739
Loper, G. B. and R. R. Pittman. Seismic recording on magnetic tape . . . . XIX 1 104

Magnetic gradiometer, The Gulf airborne. W. E. Wickerham . . . . . XIX 1 116
Magnetic tape, Seismic recording on. G. B. Loper and R. R. Pittman . . . . XIX 1 104
Magnetometer profile from Portland, Oregon to Albuquerque, New Mexico, Airborne. W. B. Agocs, J. C. Rollins, and E. Bangs. . . . . XIX 2 270
Mamou Field, Evangeline Parish, Louisiana, Geophysical history of. D. Ray Dobyns and W. B. Roper . . . . . XIX 3 490
Mapping nearly vertical discontinuities by earth resistivities. Ö. Logn. . . . XIX 4 739
Martin, Rodolfo. Gravity maxima corresponding with sedimentary basins . . XIX 1 89
Matjasic, Wallace L. Case history of Wild Goose Gas Field, Butte County, California . . . . . XIX 3 509
McCarver, Holland C. Geophysical history of the Good Field, Borden County, Texas . . . . . XIX 4 791
McGehee, F. J., Jr., Propagation of radio frequency energy through the earth . . XIX 3 459
McKay, A. E. Review of pattern shooting. . . . . XIX 3 420
McLaren, Robert Lee, Memorial . . . . . XIX 1 173
Membership list, SEG . . . . . XIX 2 382

Message from the President, A. Roy L. Lay . . . . . XIX 1 130
Method of Cagniard in seismic pulse problems, The. C. Hewitt Dix . . . . XIX 4 722
MicroLaterlog versus MicroLog for formation factor calculations. Harold D. Smith and Harold A. Blum . . . . . XIX 2 310
Model seismology, Two-dimensional. Jack Oliver, Frank Press, and Maurice Ewing XIX 2 202
Morrison, John, see Hal J. Jones . . . . . XIX 4 660
Mota, Lindonor. Determination of dips and depths of geological layers by the seismic refraction method . . . . . XIX 2 242
Mutual coupling of loops lying on the ground. James R. Wait . . . . . XIX 2 290

Nettleton, L. L. Regionals, residuals, and structures . . . . . XIX 1 1
Neumann, Leonard J.. Memorial . . . . . XIX 3 584
New horizons. T. S. Peterson . . . . . XIX 3 541
Note on downward continuation of gravity, A. Cesar A. Trejo . . . . . XIX 1 71

Oldham, C. H. G. Correlation between pre-Cambrian rock densities and Bouguer gravity anomalies near Parry Sound, Ontario . . . . . XIX 1 76
Oliver, Jack, Frank Press, and Maurice Ewing. Two-dimensional model seismology XIX 2 202
——— see Frank Press, et al. . . . . XIX 3 388
Orsinger, Albert and Robert Van Nostrand. Field evaluation of the electromagnetic reflection method . . . . . XIX 3 478

Parry Sound, Ontario, The correlation between pre-Cambrian rock densities and Bouguer gravity anomalies near. C. H. G. Oldham . . . . . XIX 1 76
Pattern shooting, Review of. E. A. McKay . . . . . XIX 3 420
Performance of resonant seismometers. William L. Donn, Frank Press, and Maurice Ewing . . . . . XIX 4 802
Petersen, T. S. New Horizons . . . . . XIX 3 541
Pilot Knob (South), Travis County, Texas, A geological and geophysical study of. Frederick Romberg and Virgil E. Barnes . . . . . XIX 3 438
Pittman, R. R., see G. B. Loper. . . . . XIX 1 104
Pohly, Richard A. Gravity case history: Dawn No. 156 Pool, Ontario. . . . . XIX 1 95
Polynomial fitting to gravitational data and density plotting by digital computers, Least squares. Stephen M. Simpson, Jr. . . . . XIX 2 255
Potential field data, A theory for the regional correction of. Fraser S. Grant . . . XIX 1 23
Present state of geothermal investigations, The. Francis Birch . . . . . XIX 4 645
Press, Frank, Jack Oliver, and Maurice Ewing. Seismic model study of refractions from a layer of finite thickness . . . . . XIX 3 388
——— see William L. Donn, et al. . . . . XIX 4 802
——— see Jack Oliver, et al. . . . . XIX 2 202
Prize-winning essay: The Williston Basin and its exploration problems. G. E. Lukk XIX 3 572
Propagation of radio frequency energy through the earth. F. J. McGhee, Jr.. . . . XIX 3 459

Radio frequency energy through the earth, Propagation of. F. J. McGehee, Jr. . . XIX 3 459
Reflection quality, a fourth dimension. Ben F. Rummerfield . . . . . XIX 4 684
Refracted rays, Devices for the construction of. Raoul Vajk . . . . . XIX 2 237
Refraction depths calculated on a time-intercept method and break-point method, Effects of weathering on. N. N. Zirbel. . . . . XIX 4 716
Refraction method, Determination of dips and depths of geological layers by the seismic. Lindonor Mota . . . . . XIX 2 242
Refractions from a layer of finite thickness, Seismic model study of. Frank Press, Jack Oliver, and Maurice Ewing . . . . . XIX 3 388
Regional correction of potential field data, A theory for the. Fraser S. Grant . . XIX 1 23
Regionals, residuals, and structures. L. L. Nettleton . . . . . XIX 1 1
Relation between telluric currents and the earth's magnetic field, On the. James R. Wait . . . . . XIX 2 281
Residual maps, Some geometrical properties of. Charles A. Swartz . . . . XIX 1 46
Resistivities, Mapping nearly vertical discontinuities by earth. O. Lögn . . . . XIX 4 739
Resistivity data over filled sinks, Interpretation of. Kenneth L. Cook and Robert G. Van Nostrand. . . . . XIX 4 802
Resonant seismometers, Performance of. William L. Donn, Maurice Ewing, and Frank Press . . . . . XIX 4 802
Review of pattern shooting. A. E. McKay . . . . . XIX 3 420
Rollins, J. C., see W. B. Agocs, et al. . . . . XIX 2 270
Romberg, Frederick and Virgil E. Barnes. Geological and geophysical study of Pilot Knob (South), Travis County, Texas . . . . . XIX 3 438

Roper, W. B., see D. Ray Dobyns . . . . . XIX 3 490
Rummerfield, Ben F. Reflection quality, a fourth dimension . . . . . XIX 4 684
Ruston Field, Lincoln Parish, Louisiana, Exploration history (prior to the Cotton Valley discovery) of the. J. Ryan Walker . . . . . XIX 1 124

Safety is our responsibility. Bart W. Sorge . . . . . XIX 3 529
Saville, Wilson Gordon, Memorial . . . . . XIX 3 582
Schlumberger, Marcel, Memorial . . . . . XIX 1 175
Scholl, Louis August, Memorial . . . . . XIX 2 346
Seismic model study of refractions from a layer of finite thickness. Frank Press, Jack Oliver, and Maurice Ewing . . . . . XIX 3 388
Seismic pulse problems, The method of Cagniard in. C. Hewitt Dix . . . . XIX 4 722
Seismic recording on magnetic tape. G. B. Loper and R. R. Pittman . . . . XIX 1 104
Seismic refraction method, Determination of dips and depths of geological layers by the. Lindonor Mota . . . . . XIX 2 242
Seismic wave model with both electrical and visual observation of waves, Three-dimensional. J. F. Evans, C. F. Hadley, J. D. Eisler, and D. Silverman . . XIX 2 200
Seismology, Two-dimensional model. Jack Oliver, Frank Press, and Maurice Ewing XIX 2 202
Seismometers, Performance of resonant. William L. Donn, Maurice Ewing, and Frank Press . . . . . XIX 4 802
Sengbush, Raymond, see M. B. Dobrin, et. al. XIX 4 695
Silverman, D., J. F. Evans, C. F. Hadley, and J. D. Eisler. Three-dimensional seismic wave model with both electrical and visual observation of waves. . XIX 2 200
Simpson, Stephen M., Jr. Least squares polynomial fitting to gravitational data and density plotting by digital computers . . . . . XIX 2 255
Smith, Harold D. and Blum, Harold A. MicroLaterolog versus MicroLog for formation factor calculations . . . . . XIX 2 310
Sokoloff, V. M., see C. A. Swartz . . . . . XIX 3 402
Some values available to students. Lawrence Y. Faust . . . . . XIX 2 337
Sorge, Bart W. Safety is our responsibility. . . . . XIX 3 529
Spontaneous potential survey of a copper deposit at Sariyer, Turkey. Sulhi Yüngül. . . . . XIX 3 455
Style guide for GEOPHYSICS. Milton B. Dobrin . . . . . XIX 1 141
Sub-surface electrical measurements about two plane interfaces. Guy O. Buckner . XIX 2 297
Surface and near-surface waves in the Delaware Basin. M. B. Dobrin, P. L. Lawrence, and Raymond Sengbush . . . . . XIX 4 695
Swartz, Charles A. Some geometrical properties of residual maps . . . . . XIX 1 46
——— and V. M. Sokoloff. Filtering associated with selective sampling of geophysical data . . . . . XIX 3 402

Technical conference of U.C.L.A. Institute of Geophysics, Abstracts . . . . XIX 2 355
Telluric currents and the earth's magnetic field, On the relation between. James R. Wait . . . . . XIX 2 281
Theory for the regional correction of potential field data, A. Fraser S. Grant. . XIX 1 23
Three-dimensional seismic wave model with both electrical and visual observation of waves. J. F. Evans, C. F. Hadley, J. D. Eisler, and D. Silverman . . . XIX 2 200
Trejo, César A. Note on downward continuation of gravity, A. . . . . XIX 1 71
Two-dimensional model seismology. Jack Oliver, Frank Press, and Maurice Ewing. XIX 2 202

Vajk, Raoul. Devices for the construction of refracted rays . . . . . XIX 2 237
Van Nostrand, Robert, see Albert Orsinger and Kenneth L. Cook . . . . .

Wait, James R. Mutual coupling of loops lying on the ground . . . . . XIX 2 290
——— Relation between telluric currents and the earth's magnetic field, On the . XIX 2 281
Walker, J. Ryan. Exploration history (prior to the Cotton Valley discovery) of the Ruston Field, Lincoln Parish, Louisiana . . . . . XIX 1 124
Wickerham, W. E. The Gulf airborne magnetic gradiometer . . . . . XIX 1 116
Wild Goose Gas Field, Butte County, California, Case history of. Wallace L. Matjasic . . . . . XIX 3 509
Williston Basin and its exploration problems, The: Prize-winning essay. . . . XIX 3 572
Wingett, Raymond O., Memorial . . . . . XIX 2 349

Yüngül, Sulhi. Spontaneous potential survey of a copper deposit at Sariyer, Turkey XIX 3 455

Zirbel, N. N. Effects of weathering on refraction depths calculated on a time-intercept method and break-point method . . . . . XIX 4 716

CONTENTS OF
"GEOPHYSICAL PROSPECTING"

PUBLISHED BY THE EUROPEAN ASSOCIATION OF EXPLORATION GEOPHYSICISTS

Volume II, No. 2, June, 1954

*Page*

A Process of Seismic Reflection Interpretation. J. G. Hagedoorn ..... 85

Quantitative studies concerning the Vertical Gradient and Second Derivative Methods of Gravity Interpretation. Otto Rosenbach ..... 128

On the Propagation of Seismic Waves in a solid Body with Elastic after working. H. Menzel ..... 139

Zur Bestimmung von Wellengeschwindigkeiten aus reflexions-sismischen Messungen. H. Dürbaum ..... 151

E.A.E.G. Abstract Service ..... 168

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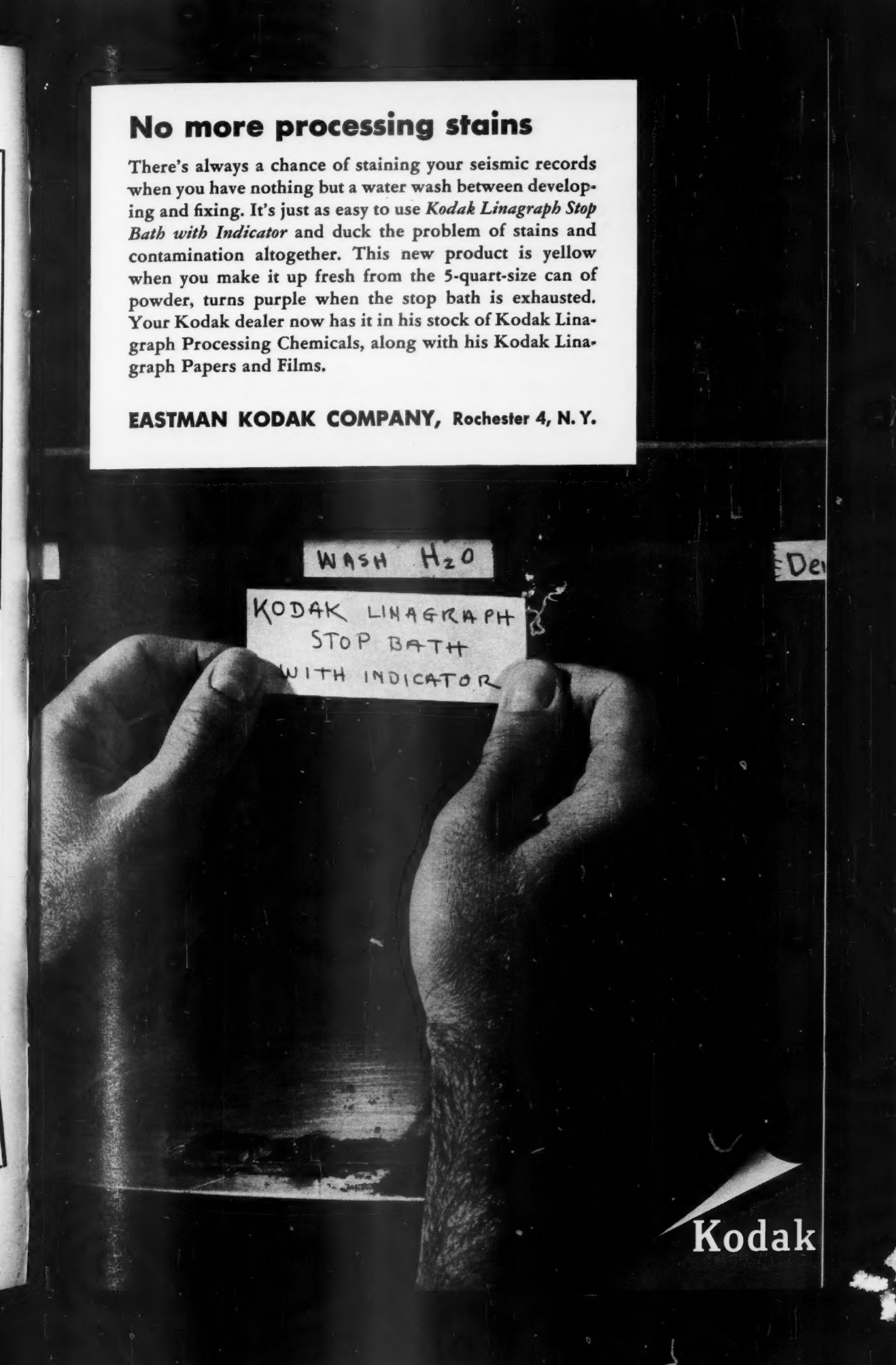

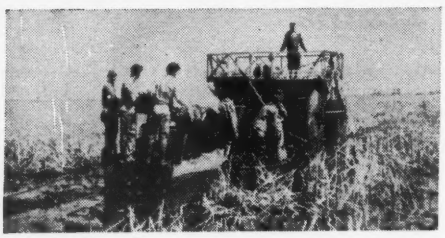

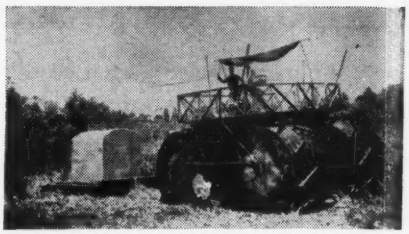

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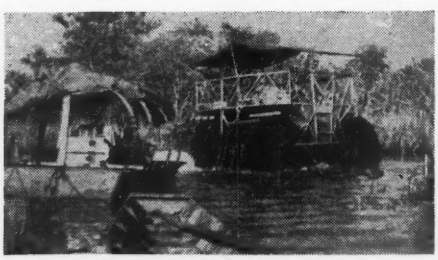

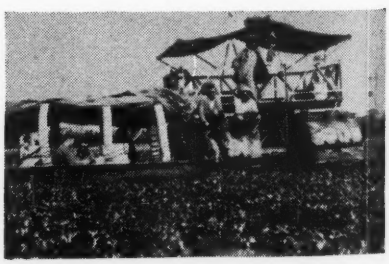

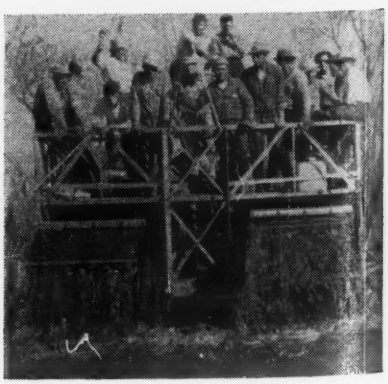

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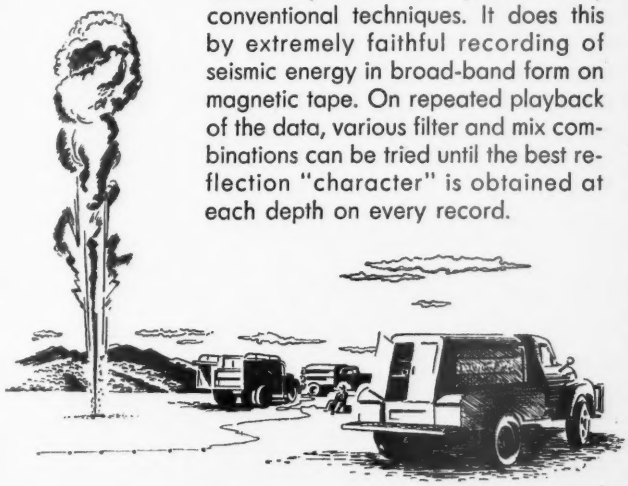

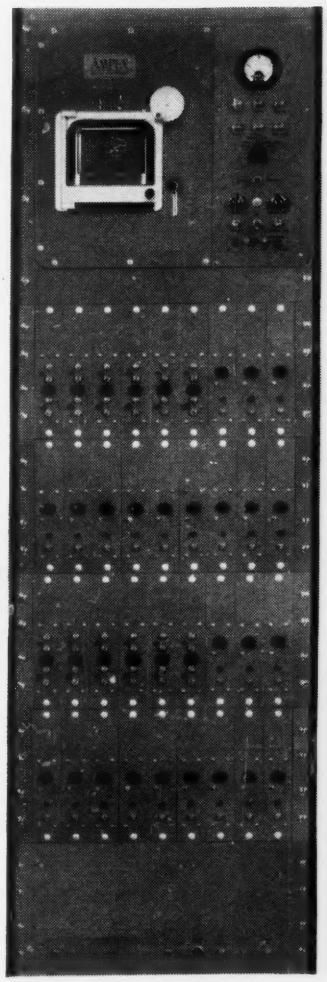

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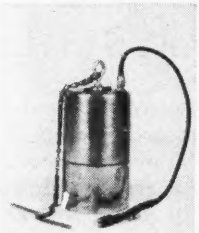

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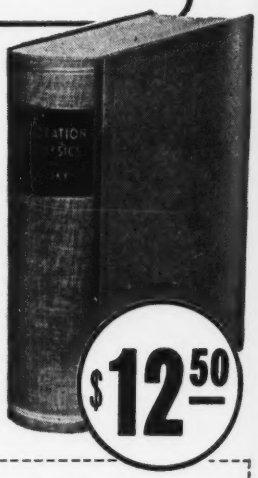

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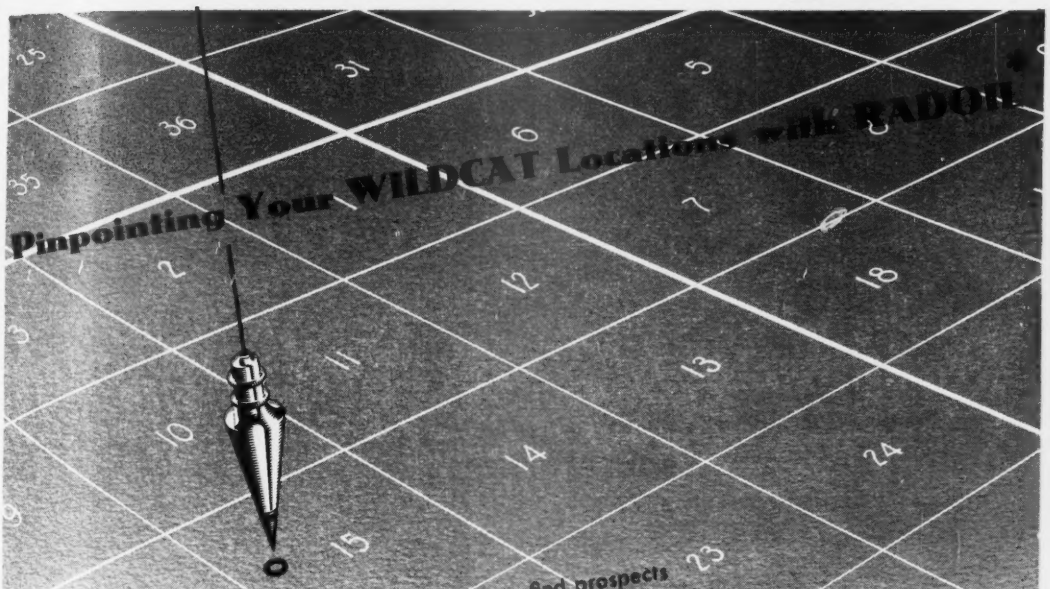

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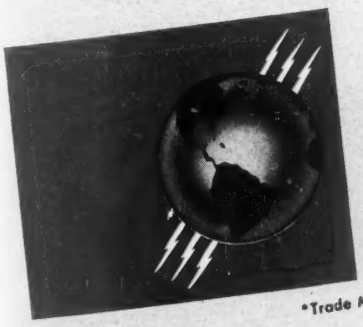

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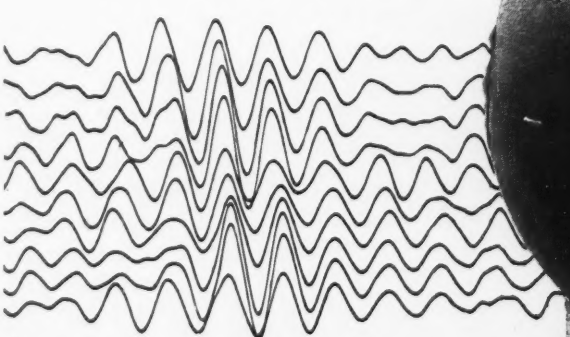

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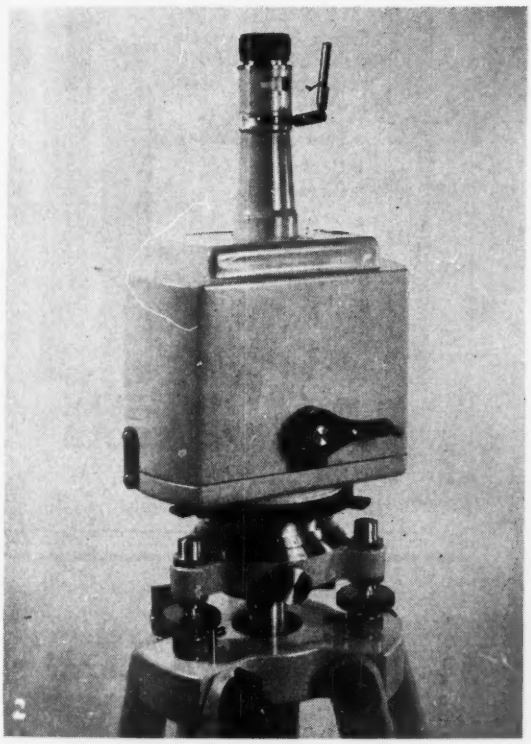

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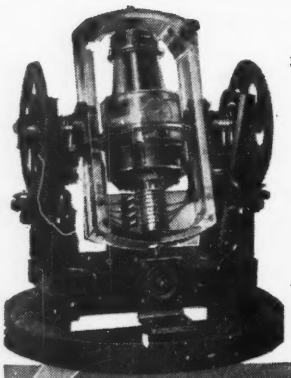
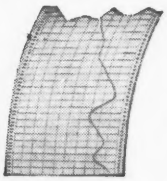
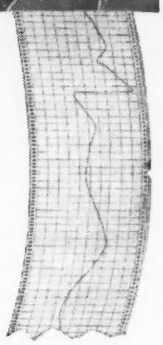




*The detector head of the magnetometer, usually called the 'bird', transmits variations in the earth's magnetic field to a graph recorder.*



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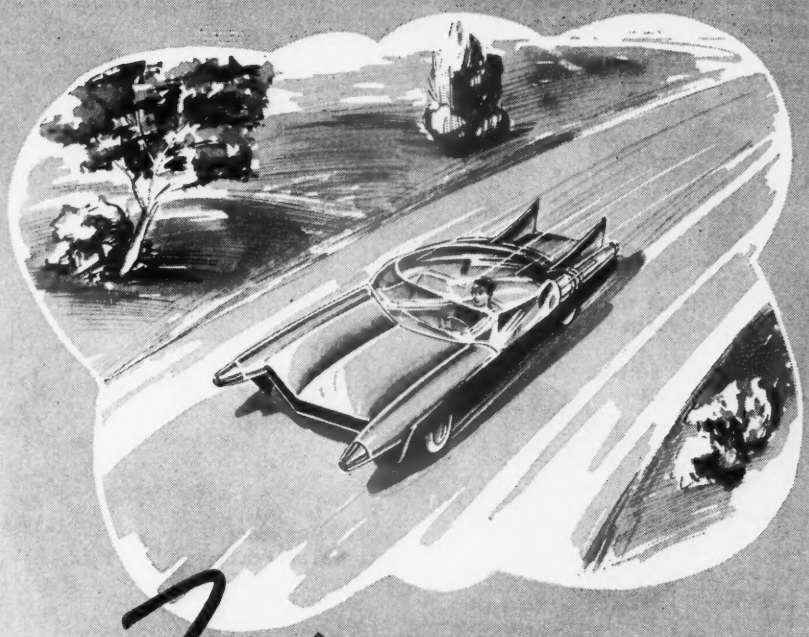

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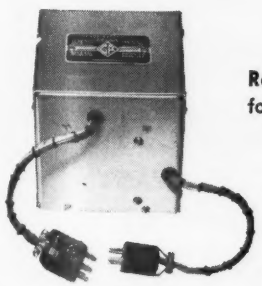

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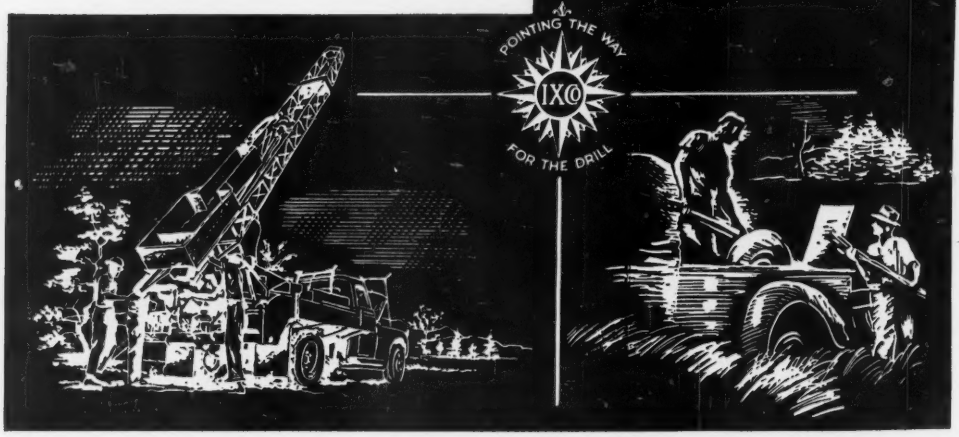


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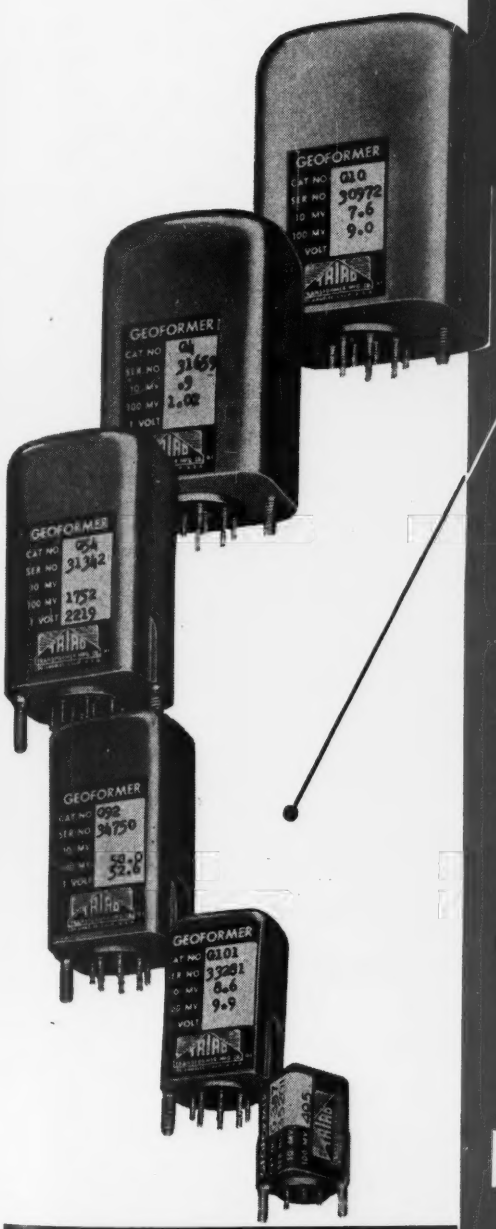


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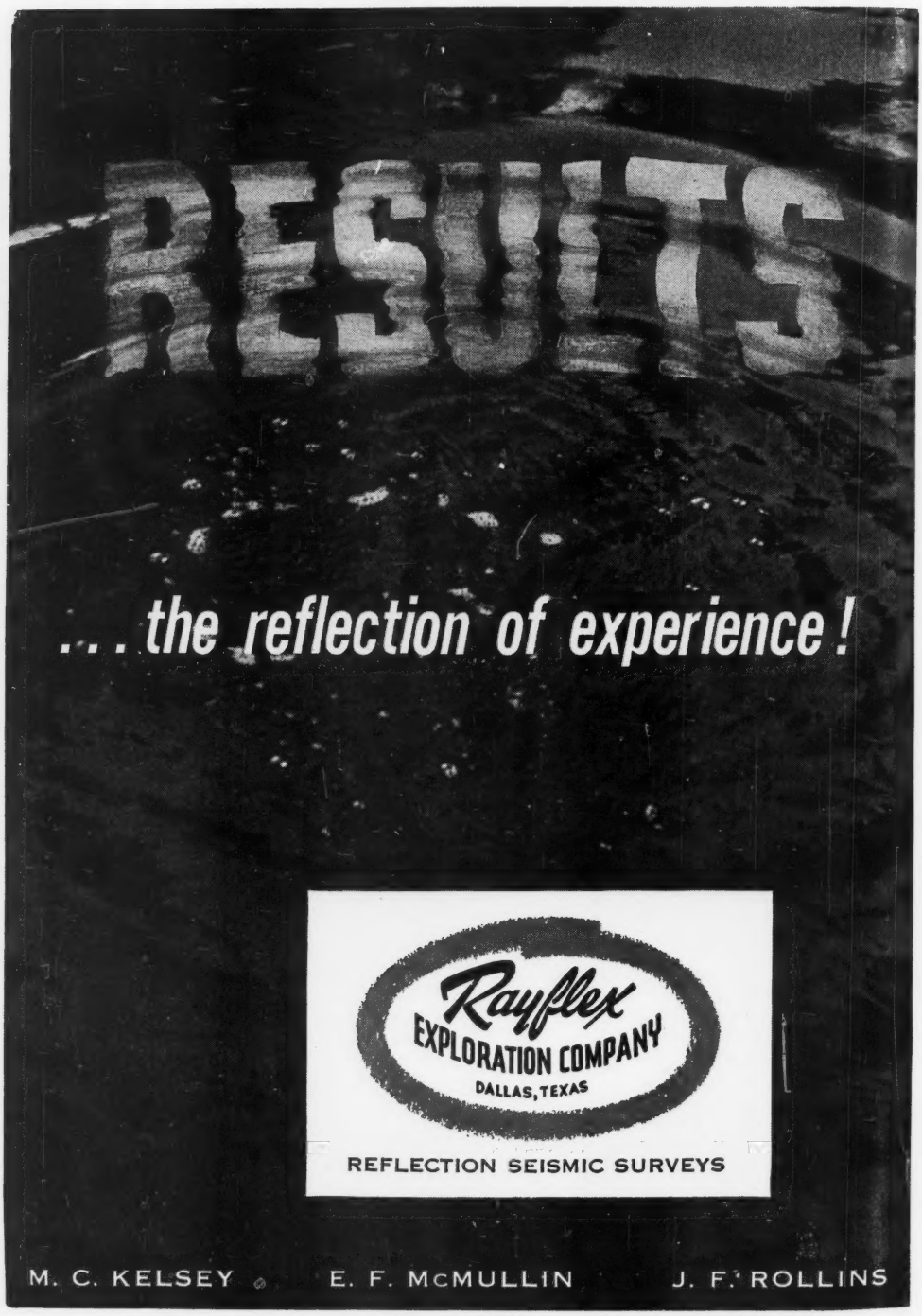
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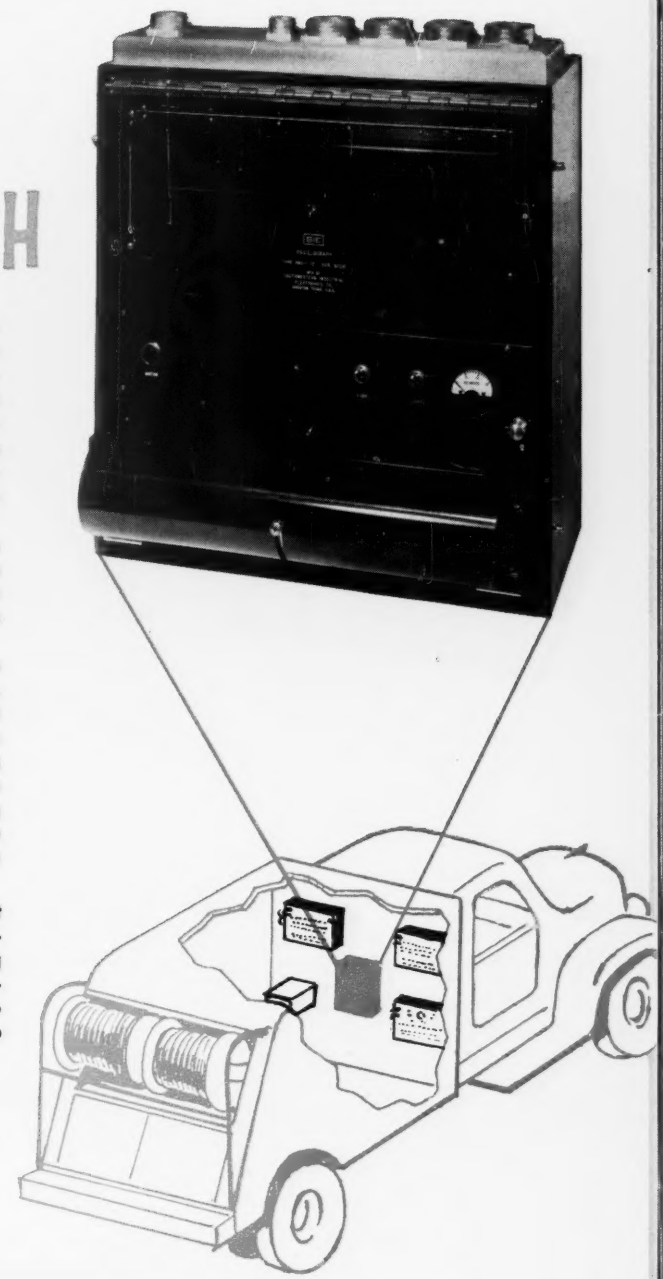

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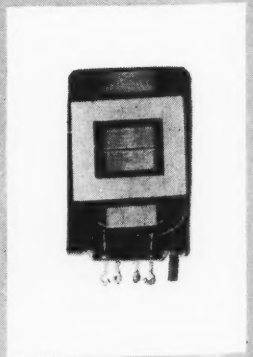

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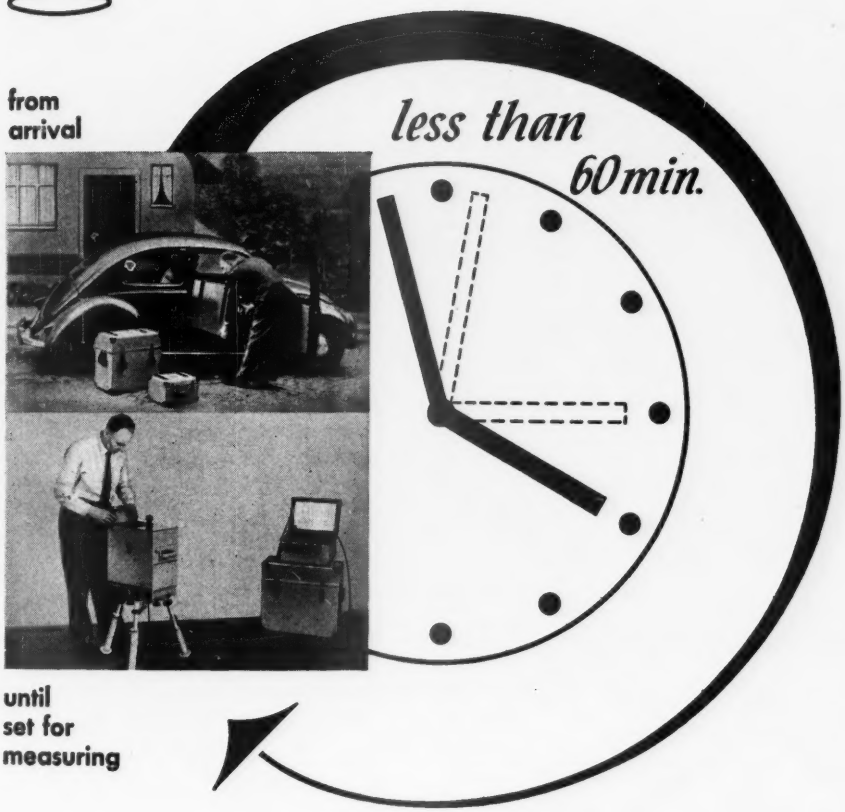


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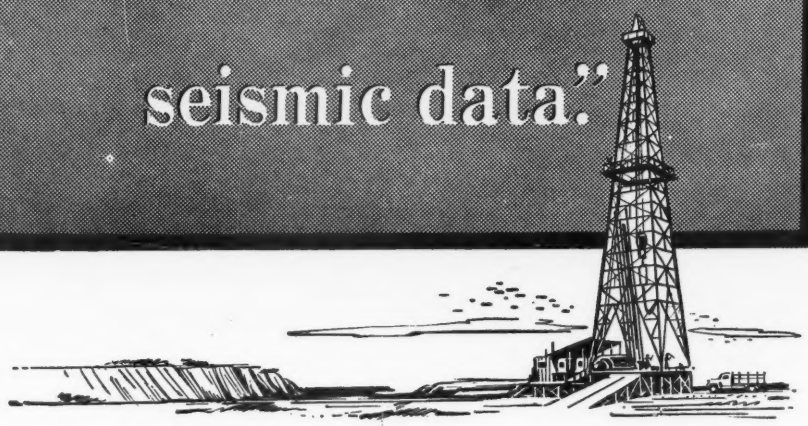

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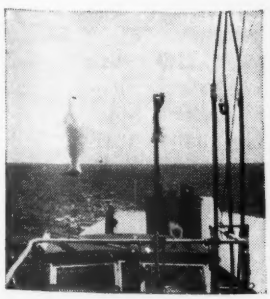

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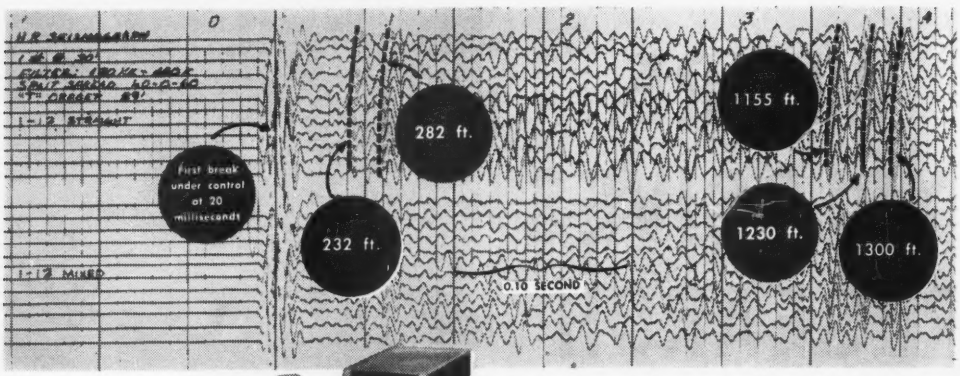


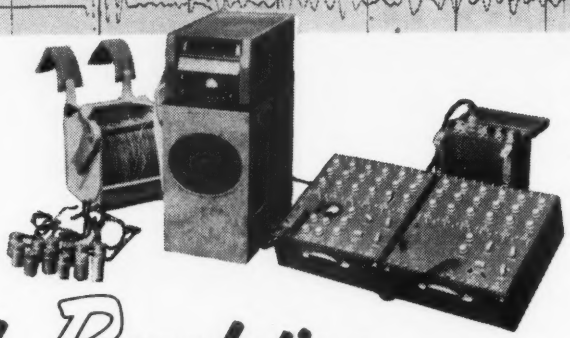

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## here's a new record for near-surface seismic data

If you're plagued with the problem of obtaining accurate near-surface seismic data, look carefully at the record illustrated here. With first breaks under control in 20 milliseconds, a reliable reflection was obtained at a depth of 232 feet. This record is typical of the results obtained by the new Houston Technical Laboratories High Resolution Seismic System. A major development in geophysical prospecting, the HTL portable HR System now makes possible reliable reflection surveys over a depth range of 100-2500 feet. It is especially designed for use in petroleum exploration, mining, ground water location, and civil engineering where shallow seismic information is vital.

## use the HTL portable *HR* seismic system to:

- establish near-surface velocity control
- obtain near-surface structural data
- supplement core-hole information

**WRITE for Technical Bulletin No. S-303 for additional information about how you can now make reliable *shallow reflection* surveys.**

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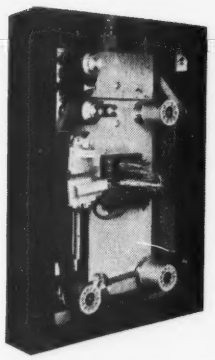

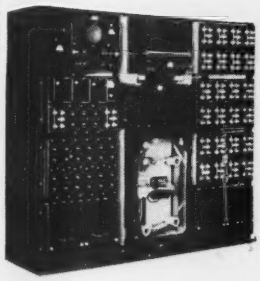

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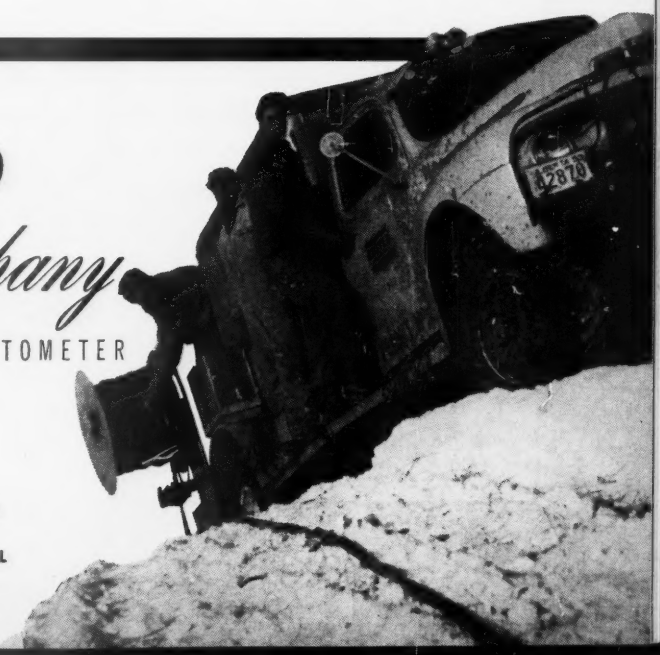

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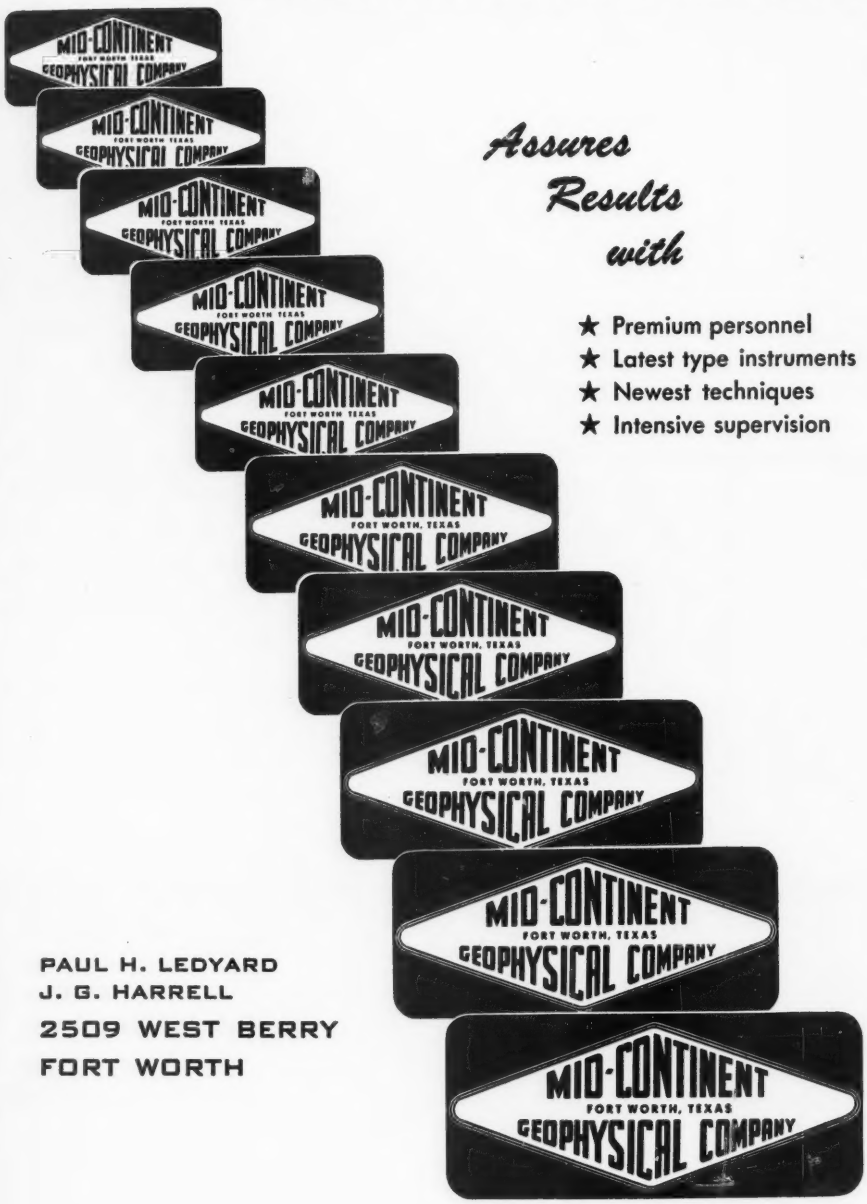


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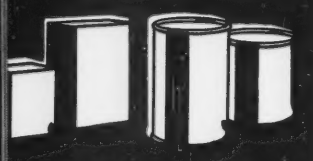

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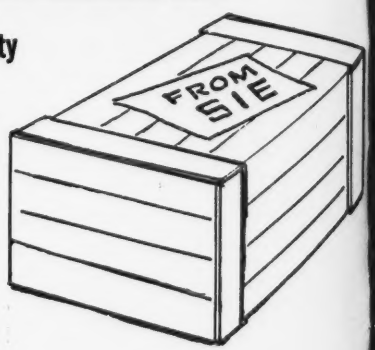


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ADC

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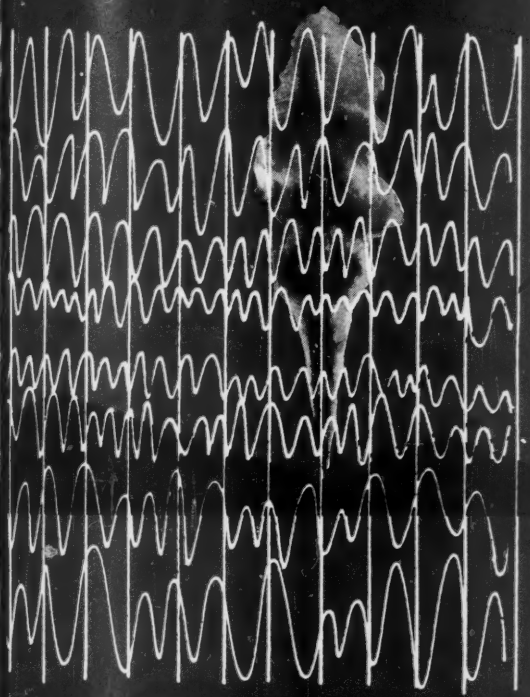

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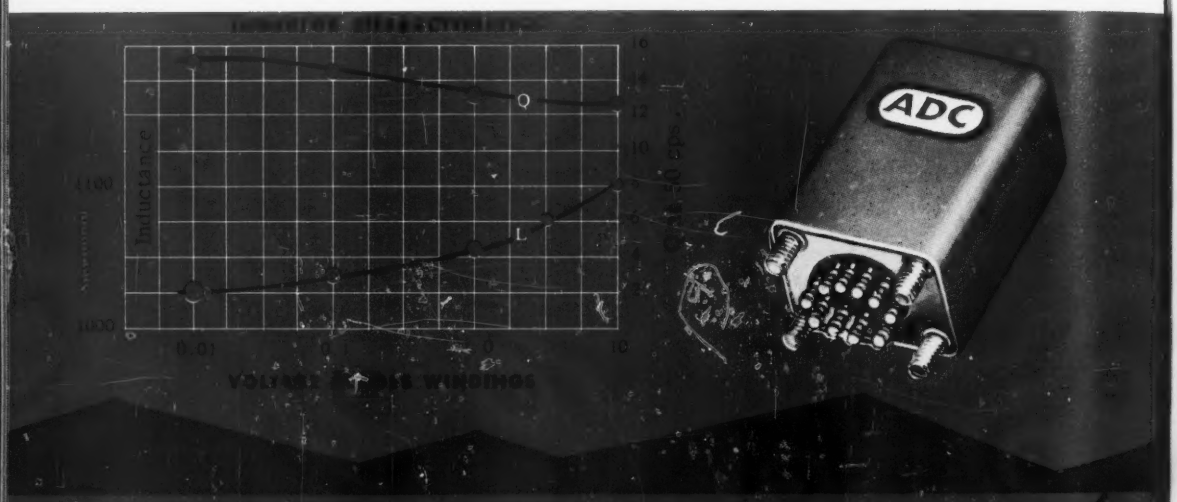
**LISTED BELOW:** are 18 typical sub-miniature transformers and chokes available as stock items in production quantities. Others may be designed to specifications for general audio and carrier frequency equipment. Power level for voice range without unbalanced DC, up to 3-5 watts, or for single tube output, up to 1 watt. All listed units in mu-metal cases except 320Y and 320Z. Curve below showing Hi-Q, low frequency inductance illustrates the unusual characteristics of a typical inductor.




# SPECIFICATIONS

## INPUT TRANSFORMERS

| Catalog No. | Primary Impedance † | | Secondary Impedance † | Primary Inductance (±5% at 10 mv 50 cps.) |
|---|---|---|---|---|
| 220A | 500 (125) ohms | to | 150,000 ohms CT | 8.5 hy. |
| 220B | 60 ( 15) ohms | to | 150,000 ohms CT | 1.0 hy. |
| 220C | 500 (125) ohms | to | 300,000 ohms CT | 8.5 hy. |
| 220D | 60 ( 15) ohms | to | 300,000 ohms CT | 1.0 hy. |

## OUTPUT TRANSFORMERS

| | | | | (±5% at 1 v 50 cps.) |
|---|---|---|---|---|
| 320A | 20,000 ohms CT | to | 16/8/4/2 ohms | 310 hy. |
| 320B | 20,000 ohms CT | to | 16/8/4/2 ohms | 1200 hy. |
| 320C | 20,000 ohms CT | to | 16/8/4/2 ohms | 1750 hy. |
| 320D | 20,000 ohms CT | to | 500 (125) ohms | 1750 hy. |
| 320E | 20,000 ohms CT | to | 50/25/12½/6.25 ohms | 1200 hy. |
| 320F | 20,000 ohms CT | to | 50/25/12½/6.25 ohms | 1750 hy. |
| 320Y | 15,000 ohms CT | to | 600 (150) ohms 2 watts | 1 db—250—15,000 cps. |
| 320Z‡ | 10,000 ohms (10 MA DC) | to | 600 (150) ohms ½ watt | 1 db—300—10,000 cps. |

## INDUCTORS

| | Inductance | Percentage Taps | Q at 0.1 v 50 cps. |
|---|---|---|---|
| 420A | 1050/800/550/400/280 hy. | None | 1050 hy.-11; 280 hy.-8 |
| 420D | 1500 hy. | 3—2% | 12 |
| 420E | 1000 hy. | 3—2% | 12 |
| 420F | 850 hy. | 3—2% | 12 |
| 420G | 600 hy. | 3—2% | 12 |
| 420H | 500 hy. | 3—2% | 12 |

Inductance of middle tap is nominal ±2% at 0.1 volt, 50 cps.

†Impedence in parenthesis indicates parallel windings ‡Single plate, all other transformers push-pull.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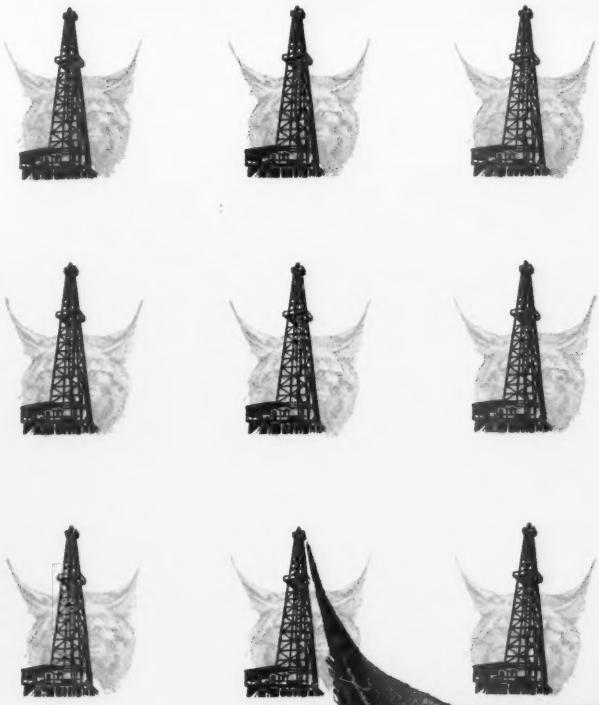

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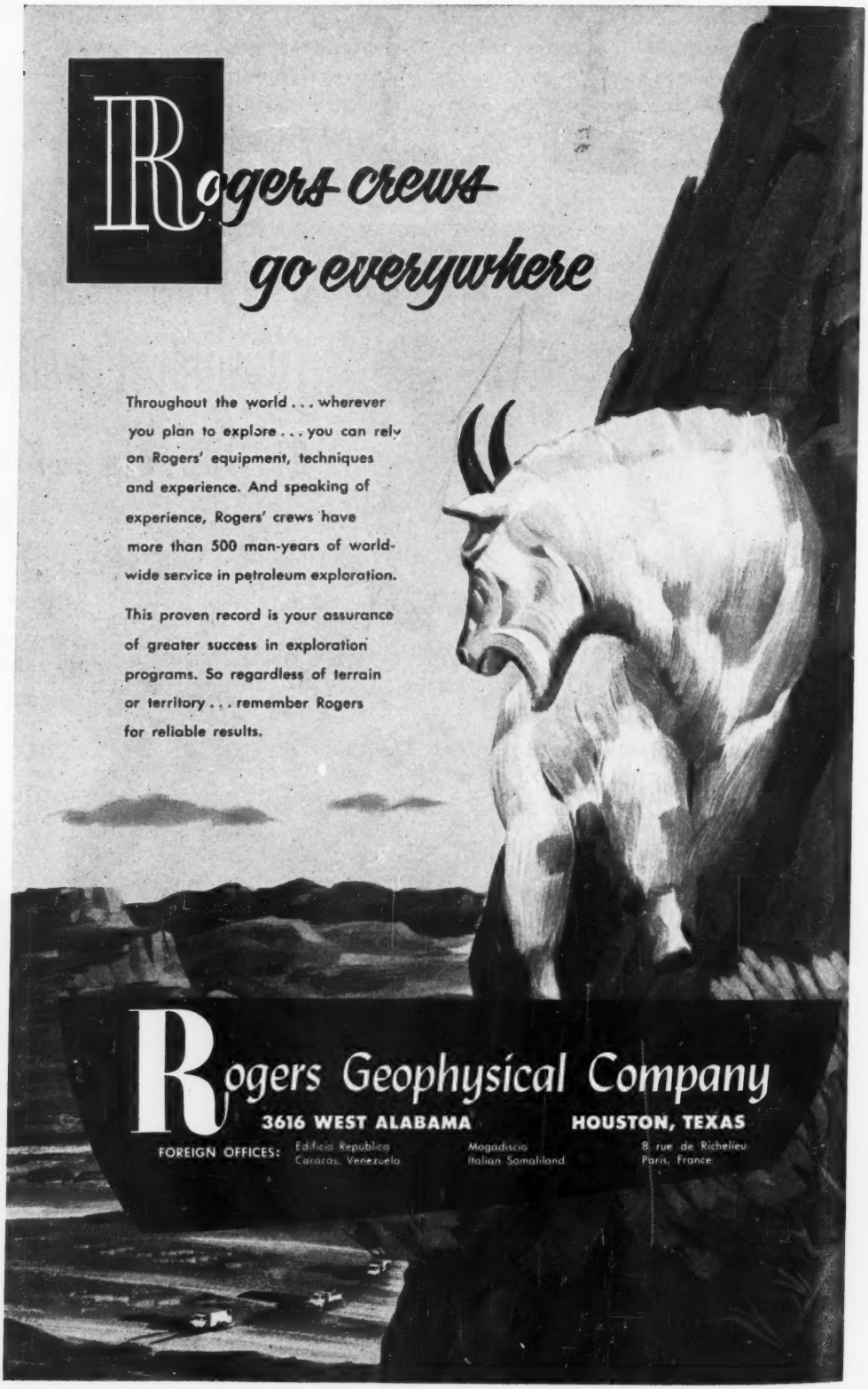
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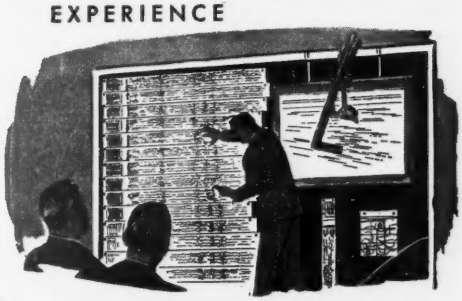

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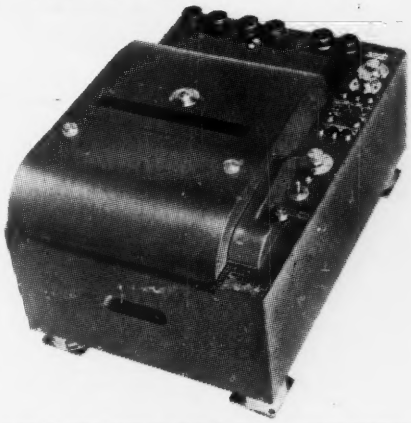

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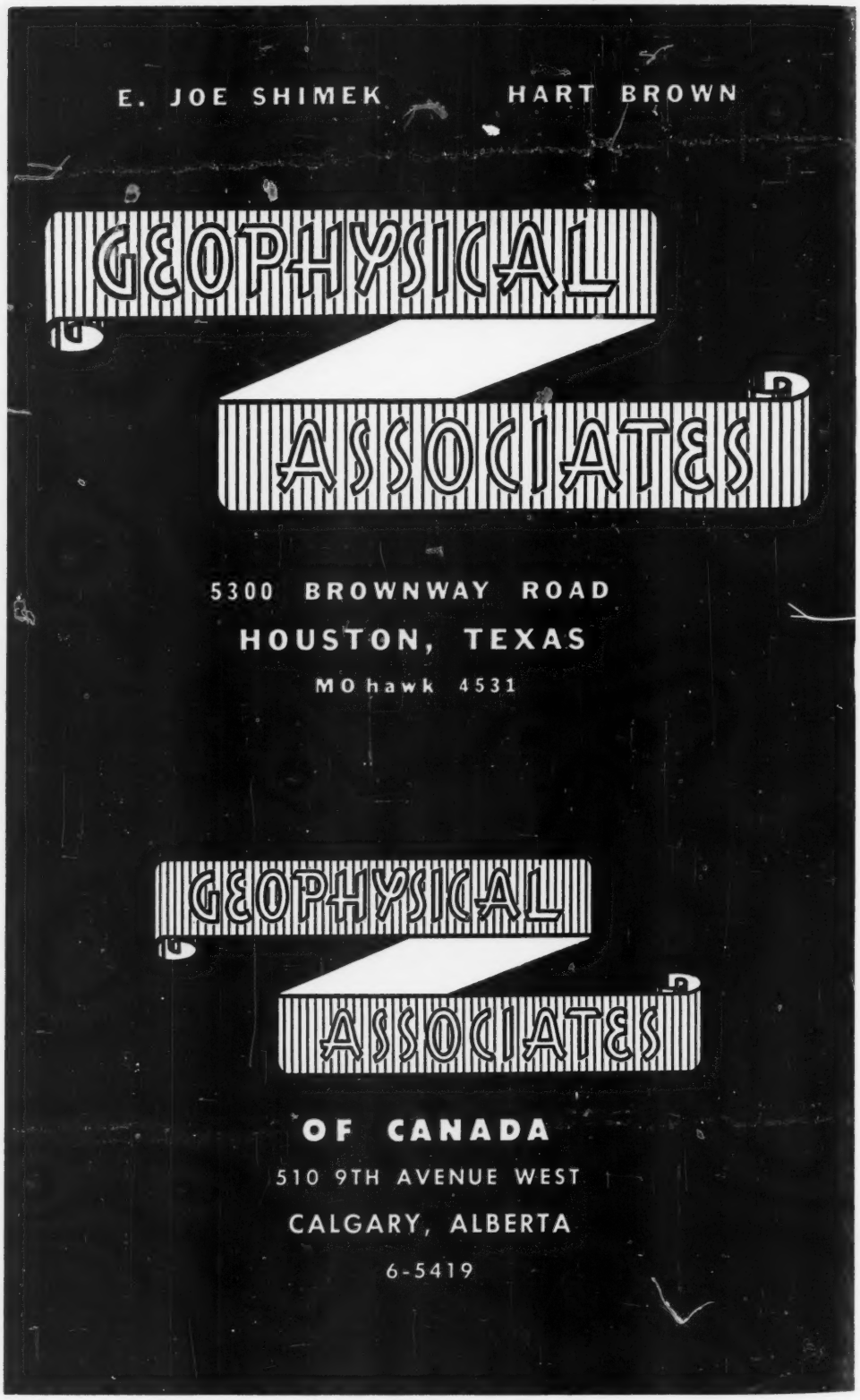
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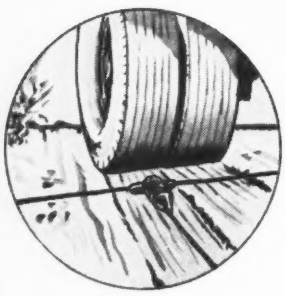

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| Month Total | $23,650.00 |
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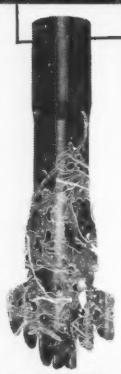
| Cost of Drills (3) | 6,000.00 |
| Other Costs, including bits | 6,233.50 |
| Month Total | $22,033.50 |
| Number of Profiles — 200 | |
| Costs per Profile | $110.16 |



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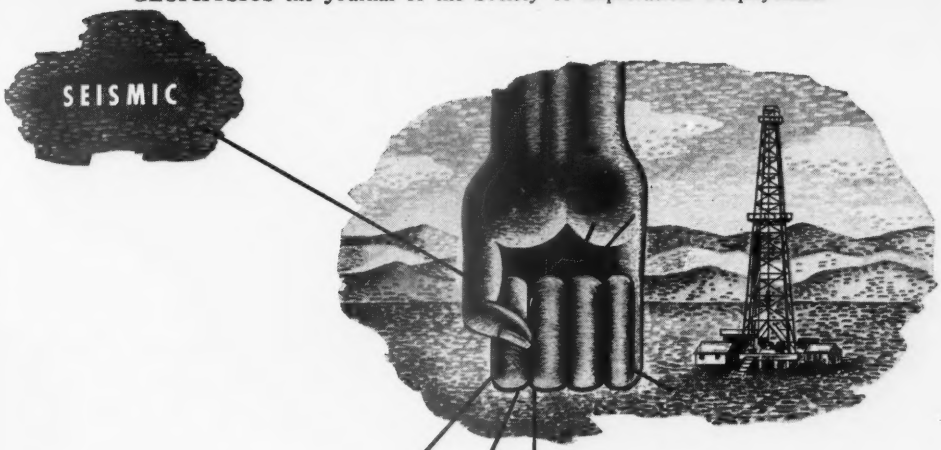


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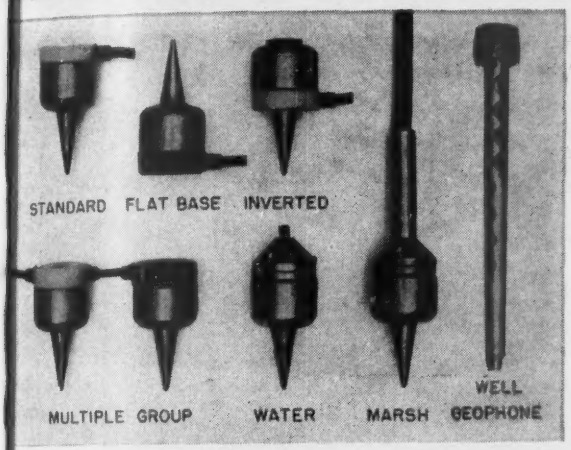


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Accessories: Plug-in top with 2 ft. lead and clips $3.50; spike $1.00; complete geophone $22.50. All prices F.O.B. Houston.

## BASIC UNIT GUARANTEED 3 YEARS

On a monthly pro-rata basis.

**MINUTE SIZE:** This geophone is ideal for multiple plants and areal spreads because of its size, weight and cost. Available as single units or in specified groups.

**DUAL SPRING SUSPENSION:** Response to lateral vibrations is eliminated, movement being restricted to the vertical plane. The two springs are used as leads for the geophone coil.

**STABILIZED MAGNETIC FIELD:** Stabilized magnet insures maintenance of precise damping and matching.

**ACCURACY:** Die formed parts, including two long springs, insure close tolerance, exact matching and continuous accuracy for the life of the geophone.

**SENSITIVITY:** Exceptionally high sensitivity and output adequate for use under all conditions—used in multiple groups or singly; for use on land, marsh and swamp; water cables; velocity and deep well surveys.

**AC ELIMINATION:** Geophone available with reversed field and coil for cancellation or rejection of power line pickup by pairing.

**INSULATION:** Protection against leakage insured by hermetic sealing and Kovar glass insulators.

**NOISE ELIMINATION:** Geophone is free from resonance peaks within the widest pass band of seismic amplifiers. Wind noise is practically eliminated due to small size and low position of lead, especially when used in inverted position.

**PLUG-IN TOP:** For ease in checking multiple groups, and replacement of leads in field; bright colored high impact polystyrene tops minimize loss of geophones and identify pairs used in AC elimination.

**REVERSIBLE PLANTING:** If surface or wind conditions warrant, geophone may be inverted with flat top placed on ground and leads reversed.

**RUGGEDNESS:** Laboratory tests and extensive field use have proven the ruggedness of this geophone. High or low temperatures have no effect.

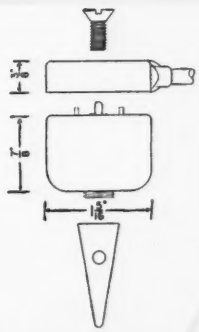
**GUARANTEE:** The standard geophone unit is guaranteed for 3 years on a pro rata basis. Within the guarantee period, any defective basic unit will be replaced at a price obtained by multiplying the number of full months in service by one thirty-sixth of the current purchase price. The guarantee covers only the basic unit for normal service.

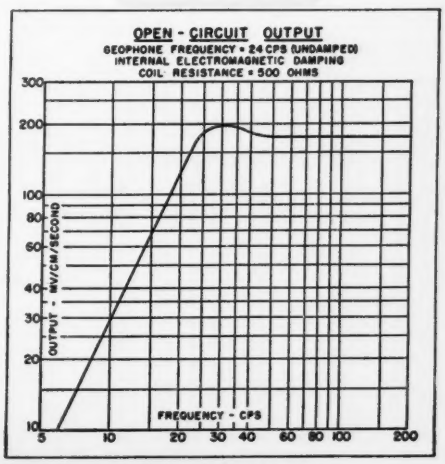
**Laboratory destruction tests, field tests, and use in many areas since 1951 have proven the superior dependability of this geophone. Top quality despite low cost. The low price and long warranty are possible because of the development of high speed tools and dies for production purposes. This manufacturing process has the additional advantage of allowing precise reproduction of identical units with perfect matching.**

**Specifications of Standard Geophone:**

| | |
|---|---|
| **SIZE:** | Geophone 1 3/16" diameter by 7/8" high; top 3/8" high spike 1¼" long. |
| **WEIGHT:** | Regular land geophone with spike and top—4½ oz. |
| **CASE:** | Brass case and spike; high impact polystyrene top. |
| **FREQUENCY:** | 24 cps; accuracy ± .25 cps. |
| **RESISTANCE:** | 500 ohms. |
| **DAMPING:** | Internal electromagnetic damping 5.5 to 1 (50% critical) into open circuit. |
| **OUTPUT:** | 185 millivolts into open circuit at 1 cm/sec. (above 3 cps). |

Inquiries invited on geophones of other specifications; geophone available for inspection and demonstration; rental and/or lease purchase arrangements offered; supplies, parts and accessories carried in stock.



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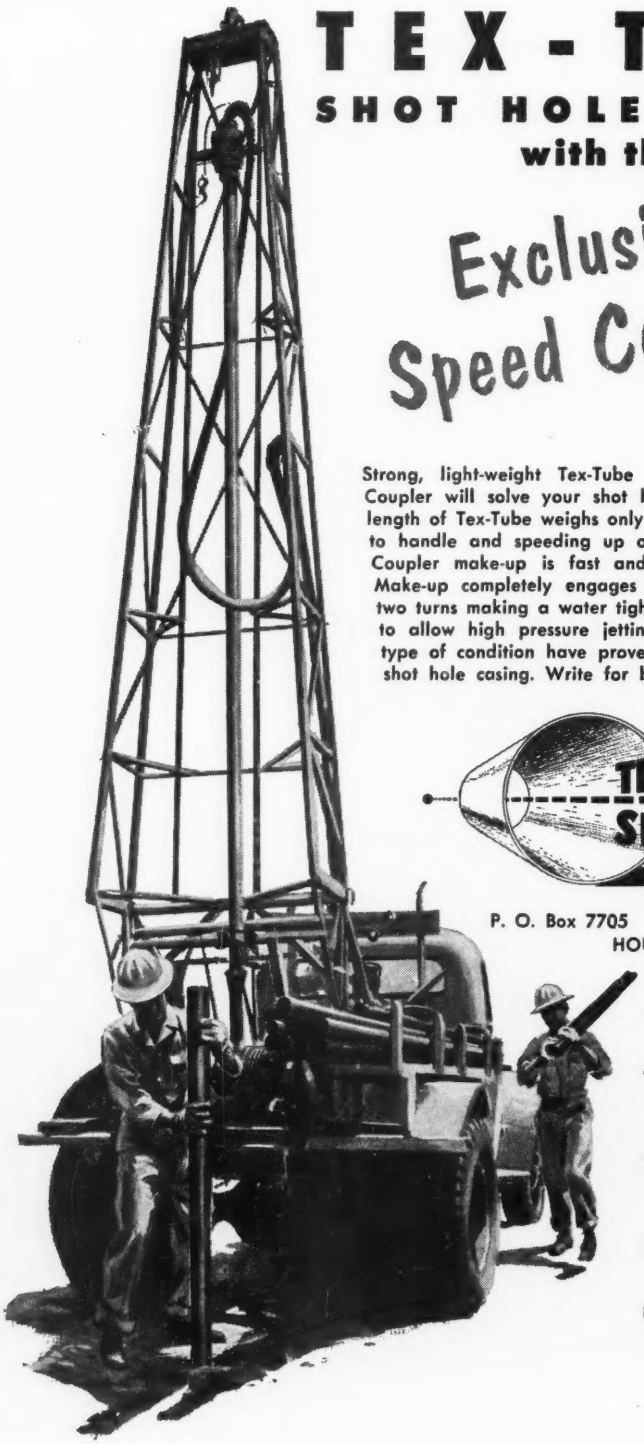

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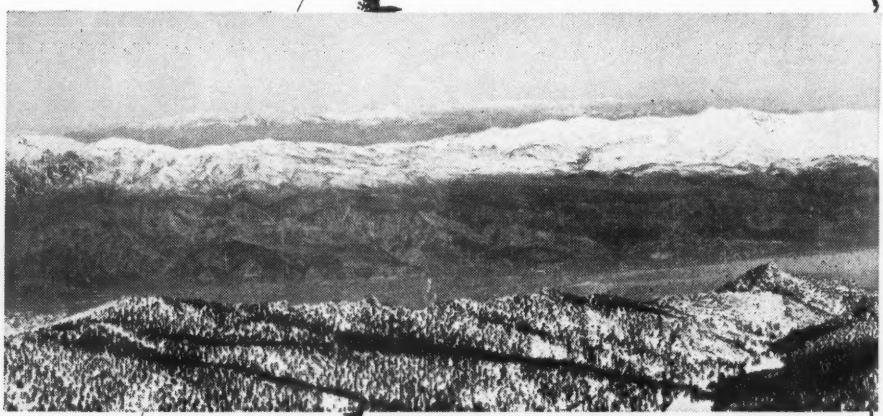

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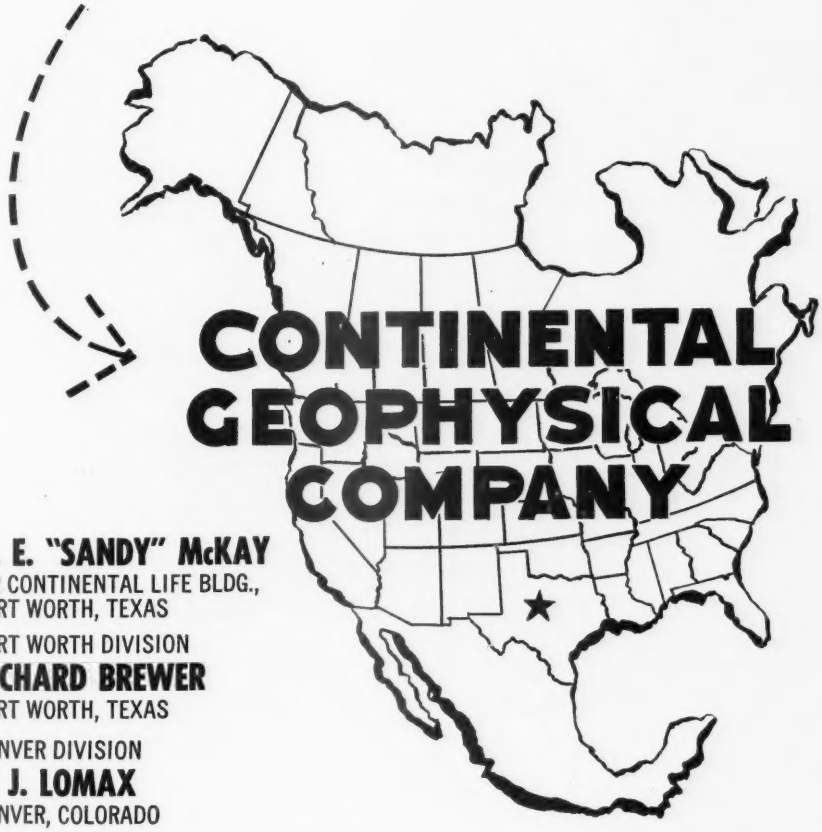

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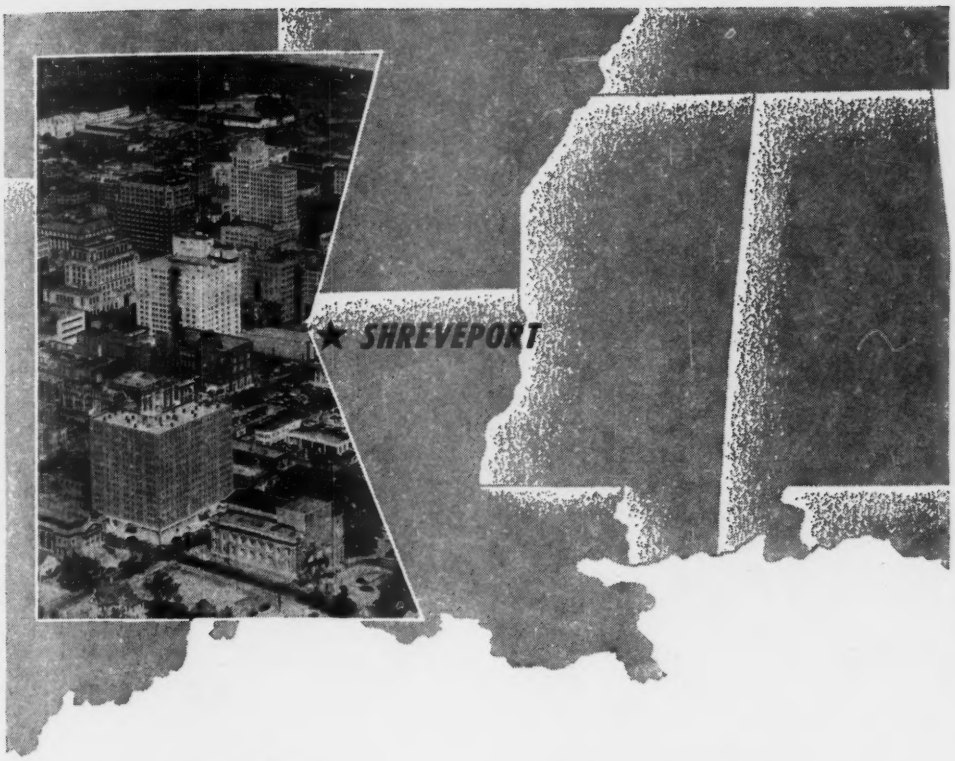


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